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DESIGN OF A TRANSONICALLY PROFILED WING

B. Kiekebusch

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SUMMARY

During a design study, we examined to what extent the application of well-known design concepts with the combined use of thick transonic profiles would lead to solutions which are optimized in terms of weight and operational costs. From the point of view of optimizing the overall functions of the wing, we felt that the usual design criteria and concepts were too restricted, and did not sufficiently represent the physical processes over the wing. Suggestions have been made for improving this situation, and a design example was worked out. Compared with a wing designed according to previously-used criteria, the new design is found to be superior in the most important functions. We have drawn the conclusion that an isobar concept adjusted to the plan form in conjunction with an "organically" designed wing will lead to the weight optimum solutions of wing profiles.

KEY WORDS: Transonic wing, isobar concepts, wing design criteria, "organic design".

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1. INTRODUCTION

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Technical concepts must be examined for the further developments of the air bus, (A 300) within the framework of an aircraft family, and future new designs of commercial aircraft. These concepts must lead to a clear improvement of the overall economy of an aircraft.

Extensive market studies and inquiries from airlines regarding their ideas about fleet composition, have shown that there is a requirement for short and medium range aircraft types. A sufficiently fine graduation of the passenger capacity is required. The commonality of components, service, and maintenance is another side condition. This means that aircraft manufacturers must restrict themselves to family concepts. Compared with previous requirements, this requires a larger design flexibility. This is especially true for a mission spectrum and the required aerodynamic design. It can be assumed that the economy of a commercial aircraft (a single design) is essentially determined directly by takeoff weight, payload weight, fuel consumption, complexity of maintenance, reliability, procurement costs, capital costs, etc. In the following, we cannot clarify the sensitivity of aircraft economy to any of these variables. Instead, we will discuss the relationships /2 between aerodynamic wing design and the structural and project requirements, and side conditions which have a direct influence on economy. Design criteria and a simple design procedure will be developed for a base wing design, which allow a check of the aerodynamic design iterations with respect to the design requirements.

2. THE DESIGN PROBLEM

We can assume that increasing the payload fraction (savings in dead weight) and/or reducing the drag for a specified takeoff weight, range, and Mach number will remain the main goal of a design optimization for future commercial aircraft. In this sense, a design aerodynamicist is required to find a wing/aircraft geometry having an aerodynamically "optimum" pressure distribution (force distribution) within the constraints of the design requirements. In addition, it must satisfy the minimum aerodynamic properties (construction principle).

When this problem is solved, this does not necessarily mean that the wing design is optimized in the overall economic sense. Increases /3

in the payload fraction require an optimization of the design weight for any specified force distribution over the wing (aircraft). The optimum combinations of geometric design parameters (aspect ratio, thickness distribution, sweepback, engine configuration, etc.) usually do not coincide for the aerodynamic and weight (structural) optimization processes. For the overall economic optimization, only an operational cost calculation can give the necessary information about the most important design parameters, and their optimal combination.

During an iteration optimization, the important design restrictions are defined by the aerodynamic performance limits of the wing, and the design aerodynamics and project aerodynamics, which leads to the desirable optimum combinations of design parameters. In the present design situation, we expect substantial improvements in the overall economy using a transonically-profiled wing (increase in the area loading, thickness increases). A transonically-profiled wing with favorable aerodynamic properties has already been built for the A 300 B [1]. The calculation procedures and the experimental results have led to much new information about transonically-profiled wings. We have gained more information about the useful performance range. We are certain that a further and new development of commercial aircraft will take place during the beginning of the 1980's, and will result in a substantial expansion of previously-specified or unclear performance limits. /4

2.1 Preliminary Optimization of Aspect Ratio and Thickness

2.1.1 Results of a Project Design Variation

The dependences between economy and aerodynamic functioning of a wing are the points of departure for all of the design work, which is specified by the overall project.

Here there is a direct connection between economy, wing aspect ratio and wing thickness, and quantitatively this has not yet been sufficiently clarified for the transonically-profiled wings of differing thicknesses. During a project parameter study, we carried out a preliminary optimization of wing aspect ratio and profile thickness for a current aircraft type ((Airbus B 10-type), in order to obtain information about a cost optimum parameter combination [2, 3].

Starting with the basic design, we investigated the influence

of aspect ratio and profiling of different wings on the resulting design. In addition to the engine position and the designed mission, we also fixed the takeoff and landing path requirements, so that different aircraft result depending on size and payload capacity. The corresponding design weights and fuel consumption rates were related to the number of passengers. In this way, we obtained information about favorable and unfavorable wing concepts. By connecting the two /5 cost factors in an overall operational cost calculation, we can obtain information about economy. When transonically-profiled wings are used and which therefore results in possible average wing thicknesses of $(D/L) = 15\%$, one finds that economic wing aspect ratios are between $\Lambda = 10-11$. Thinner profiles are less economical because for the specified sweepback (here, $\varphi_{25} = 25^\circ$) and area loading, cruise Mach numbers are possible which are not required here. The important results for aerodynamic design can be found in Figures 1-3. Figure 2 shows a summary of the results of this investigation for the present design case with the aspect ratio $\Lambda = 9.5$ and a sweepback of $\varphi_{25} = 25^\circ$. We find from this that even if one assumes the same gains in operating costs, there is a savings in the operating empty weight/passenger ratio for large profile thicknesses for a wing with an average thickness of $(D/L) \geq 0.135$ using relatively conservative assumptions regarding the structural weight advantages.

For equal or slightly-increasing fuel consumption ratios per passenger, however, this maximum "economic" average wing thickness is between $(D/L) = .15$ (1200 nm) - $.16$ (500 nm) depending on range, which seems to be realistic if one considers the operational empty weight which can be used for large wing thicknesses.

2.1.2 Structural Weight and Wing Geometry

The operational cost calculation of the previous section resulted in relationships between the wing aspect ratio and the average /6 wing thickness. However, this data is not sufficient for establishing differentiating geometric side conditions (for example, thickness distribution) for a weight-optimum wing design. We are still missing information for the determination of the average wing thickness. The required information is obtained for strength investigations for the specified wing geometry using the load cases which determine the dimensions.

Figures 3-5 give the results of a strength analysis for a specified wing type which corresponds to the present design case.

Figure 3 [2] very clearly shows the strong dependence of wing weight on wing aspect ratio on average wing thickness. We can see the weight-optimum limiting thicknesses here. From strength calculations, and for a specified wing geometry, we can define an average wing thickness, which is composed of wing segments which are representative of the structural complexity and have the corresponding weighting factors. For the wing planned form geometry of interest here, and for a representative load case, we have found that the following definition of an average wing thickness (equivalent thickness) [5], is a useful one:

$$(\bar{D/L}) = 0.6 (D/L)_{\text{ROOT}} + 0.3 (D/L)_{\text{KINK}} + 0.1 (D/L)_{\text{TIP}} \quad (1)$$

For a specified "economic" wing thickness, the relationship (1) can be used as a first requirement for the thickness distribution as a function of the span over the wing. From the weighting distribution of the representative wing thicknesses, it becomes clear that the weight savings is determined almost exclusively from the thickness distribution of the inner wing, because of the large height. The outer part of the wing has only a small influence, and also has the representative aerodynamic profile. Substantial weight savings from the outer wing (sheared wing) will more likely come about by increasing the area loading there, by increasing the lift load of the profiles installed there, in conjunction with a reduction of the wing area. However, one must decide whether to exploit this possibility using the present wing plan form and the selected design lift distribution. Up to now, we have discussed the average wing thickness. Here, we mean a thickness which is representative structurally for the entire wing. In addition to the thickness steps in the span direction, we also consider a distribution in the chord of the wing direction, which corresponds to the average spar height of the supporting wing box structure.

If the wing box structure position is known for a specified wing plan form geometry, by using the thicknesses to be determined as a function of span according to (1), one obtains a first impression about the distribution about the weight optimum box structure cross-sections.

However, one must have an idea about the aerodynamically-feasible limiting thicknesses (drop thicknesses).

The selection of suitable profile drops (profiles) for the specified wing plan form must consider at least the feasibility of the main dimensions of the wing box structure cross-section (average spar height, box structure depth). At least in the wing areas which are most sensitive to structural weight (inner wing) when carrying out a weight optimization.

Wing cross-sections or profiles which do not conform to this /8 must be looked upon as non-"weight optimum" (Figure 6), as far as their thickness is concerned, even if they satisfy the desired largest profile thickness requirements.

Additional structural advantages result from this in addition to a direct influencing of the wing box structure weight by selecting a thickness distribution which is matched to the structure. This leads to further savings in structural weight of the wing.

Figure 4 shows the most important structural advantages of a thick and transonically-designed wing. A table of the wing structure weights is given for a design example (B 10 X) with the various wing thicknesses which can be realized. Figure 5 shows various thickness distributions ($D/L(\eta)$) over the span for the design example already mentioned. The lowest curve assumes the first project assumptions. The top curve considers the structural recommendations for saving weight. The broken curve indicates the compromise based on aerodynamic and other design limitations.

2.2 Aerodynamic Considerations for Realization of Thick Wings (Profiles)

We can roughly formulate the tasks of the design aerodynamicists resulting from the previous discussion as follows: for a specified lift requirement, a wing must be designed with consideration of its flow-physical limiting regions and a realistic maximum thickness must be determined. This means a "thickness/lift optimization" for the wing as far as the structural weight advantage is concerned (increase of the net lift equals payload increase) with the side conditions of the smallest possible drag. For the transonically-profiled wing, there is not yet sufficient quantitative information, and therefore the design aerodynamicist must base his work on empirical and intuitive methods.

In order to obtain an idea about a wing design, it is useful to consider the basic relationships between wing thickness, pressure distribution, and the fluid dynamic limitations.

For the wing having an average or large aspect ratio, and for an overcritical profiling, we assume here again that the aerodynamic wing characteristics can be reduced to characteristic profile flows, for the most part.

The basic ideas about the influencing of thickness profiles by /10 an appropriate selection of the design pressure distribution are also applicable to the wing discussed here.

2.2.1 Orientation Aids for Thickness Limitations

According to [9], it has been found practical to associate the suction side pressure distribution with a special transonic drop geometry, which also makes sense in regard to the usual isobar concepts [10, 11].

By locally changing the thickness of the profile underside, using conventional design techniques of subsonic profile theory, we can realize the desired lift requirements [7].

The problem of influencing the thickness of a transonically-designed profile can be approximately reduced to the design of a profile drop and a skeleton line [9, 12]. This clearly facilitates the definition of a suitable design pressure distribution in our design task.

The association of a drop pressure distribution and a suction side pressure distribution over the wing means a substantial influence on the thickness distribution of the wing. Also, there is a strong influence of this drop pressure distribution type on the fluid mechanical limiting loads on the wing (subsonic separation tendency, C_{Amax} /11 without flaps, shock/boundary layer, separation tendency, etc.).

In order to achieve the desired profile thicknesses or to evaluate the selected pressure distribution type regarding its influence on the thickness distribution and the achievable limiting thicknesses, information is required about the influence of the individual pressure distribution parameters on these target values.

According to Figure 7, the most interesting pressure distribution types of transonic profiles can be described roughly using four characteristic ranges:

- the level of the pressure minimum, c_{pmin}
- the setback of the point of beginning of recompression, x_R/L
- the size of the local supersonic region c_p^* , x_{s1} , x_{s2}
- the trailing edge pressure c_{PHK}

It can be assumed that these pressure distribution parameters will give a good description of the drop thickness of the type of thickness distribution which depends on the chord. In collaboration with the DFVLR [13, 14], we were able to evaluate the results shown in Figure 8 for simple transonic drop pressure distributions and a simple case with lift. However, these are only the first rough relationships and can be used for selecting a suitable design pressure distribution. Additional boundary layer variations for transonic profiles have been established by Boerstoeel [15], and are shown in Figure 9.

2.2.2 Aerodynamic Profile Load and Profile Thickness

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The requirement for a large profile thickness and a large profile lift means a substantial load on the suction side, which is restricted essentially by the required working range limit (off-design behavior). The design pressure distribution which is important is the one for the maximum speed design (M_{MC}), which in the final analysis also determines the base profile of the wing. In a study on optimum recompression, Sonnleitner [16] pointed to the basic research of A. M. O. Smith [17], etc.. He found a type of pressure distribution which is favorable for this range (as far as recompression and lift for the off-design behavior is concerned), which leads to a modified isobar concept when applied to the wing.

The analysis essentially proceeds from an aerodynamic optimization of the glide coefficient for the profiles or the wing. However, this is probably not sufficient for a consequent optimization with regard to economy (net lift). In order to obtain a realistic evaluation of the "glide coefficient" (for payload), in any case structural modifications which are required for improving aerodynamic performance of the wing should be taken into account in the calculation of the useful lift to total drag calculation. This is not so true for the high-speed range using a "clean wing", but is more true for a "low speed wing" with its typical high lift aims. Bielefeldt [18-20] systematically evaluated a large number of high-lift measurements using wings with

flaps. He found a substantial dependence between the thickness of the /13 fast flight profile and the useful additional lift caused by a certain flap system (Figure 10, 11).

It was found that by selecting the profile thickness (thickness distribution) and the high lift aids (single, double, triple slotted flaps) the useful additional lift values become optimum in the direction of increasing profile thickness. Also, one can count on a substantial reduction in the weight of the flap installations. Our own measurements with a 17% thick transonic profile have confirmed this tendency [20]. For the high-speed range, we can dispense with minimizing the profile drag for optimum recompression, if the profile thickness distribution leads to better weight values.

The thickness distribution of a profile can be contrasted to the complexity of installing high-lift devices.

The additional weight in the payload weight is a factor proportional to the induced drag (square of the weight) in the calculation of the drag. The increase in the drag due to the thickness increase is linear, according to Truckenbrodt [21].

We define the following simple relationship between the lift and the drag as the "effective" glide coefficient:

$$\frac{A_{eff}}{W} = \frac{(C_A - \Delta C_A \text{ MEHRGEWICHT})}{C_{WR} (1 + K_0 \cdot \frac{D}{L}) + K_1 (C_A + \Delta C_A) + K_2 (C_A + \Delta C_A)^2} \quad (2)$$

where ΔC_A is a aerodynamically-required additional weight* (high lift /14 system), then we have not yet found a quantitative description of the problem, but we can derive a design for the aerodynamicists: the aerodynamic possibilities of a thick profiling must be exploited completely over the entire working range of the wing, in other words, an "organic" wing must be optimized [22].

2.2.3 Design Check of a Profile Thickness

Once certain design criteria have been decided upon for a design pressure distribution, the base profile geometry can be determined using well-known transonic design procedures [23, 24].

In the applications of the profile and in order to maintain the profile thickness, it is important to ensure that the required working

*Translator's note: mehrgewicht equals "additional weight".

limits of the profile are satisfied (wing). We will examine this for the design example presented using a suitable recalculation method [25, 26] with a coupled boundary layer calculation. If the working limits are not reached, it is necessary to influence the variation of the recompression over the profile in the positive direction (pressure gradient, trailing edge pressure, trailing edge angle, profile thickness).

The profile can be modified in the trailing edge region, during an iteration. When calculating the limiting working range, a contour correction is derived from the variation of the boundary layer displacement thickness extended beyond the separation point on the profile upper side and its linear continuation to the downstream base point of the sonic line. After smoothing it is applied to profile contours on the top side and the bottom side. /15

$$x \geq x_R$$

$$\Delta z(x) = \frac{\delta_1(x) - \delta_1(x)_{LIN}}{2}$$

with

$$\delta_1(x)_{LIN} = (\delta_1)_{x_R} + (\delta_1')_{x_R} (x - x_R)$$

$$z_0 = z_0 + \Delta z$$

$$z_k = z_k - k \cdot \Delta z \quad ; \quad -1 \leq k \leq 1$$

When the trailing edge is redefined, with consideration of the contour filling, Δz , one then uses the extension of a skeleton line.

2.3 Wing Concept

During an operational optimization of a wing, the design aerodynamicists must consider structural weight gains during wing design; more than previously. The classical problem formulations for wing design for fast flight such as maximum speed, "drag rise" limit, mission range, "buffet" limits, etc., are expanded here by the optimization parameter "wing thickness distribution". It may be advantageous during the first design steps to specify certain wing areas for positive gains in thickness, and to assume a realistic maximum value for the thickness distribution during wing preliminary design. The possibilities of developing a weight-optimum high lift system from the specified wing should

be just as important as the purely structural weight gains brought about by modifying the height in the wing box structure. This is very /16 important because the wing area is an important parameter which determines the weight and is already specified by the given takeoff performance values. The special geometry of thick transonic profiles offers new possibilities compared with conventional and more slender profiles. Considering the high lift investigations of Bielefeldt [18-20], we see that an optimum adjustment of the fast-flight profile to the desired high lift performances can be achieved by curving the top side of the profile. By matching the fast flight performance and the low speed performance of a profile design, we can bring about an organic development of a high-lift system from a high-speed wing. This design possibility should be used always in transonic wing design; even subsonic. Unfortunately, this has not been done as much as for the fast flight performances. Assuming a "linear" development of the wing, from base profiles, the basic requirements mentioned above will become involved in the basic profile design.

The following are areas of "potential" weight savings:

- the entire inner wing in the chord and span direction (height at the wing root, tank volume, landing gear storage, high-lift system, etc.)
- the wing box structure region has an important supporting member over the entire span
- the rear box structure in the flap field region
- the nose box structure in the wing topside region.

At this stage of development, we have consciously accepted disadvantages in regard to the expected aerodynamic performances of the preliminary wing design. By exploiting geometric reserves, these can be equalized with only a slight modification to the wing design (primarily changes in the local thickness distribution in the front and rear box structure region).

For a weight optimum matching of the wing to specified working ranges or performances, it is recommended to first specify the wing design from the "thickness", rather than to provide for high aerodynamic reserves to begin with, which later on could not be used.

- isobar concept

The isobar concept used as the basis for wing design is very

important for the expected aerodynamic performances of the wing and the weight, considering the relationships discussed above. Sonnleitner proved that a consequent application of the "straight isobar" concept to a pointed swept wing does not represent an optimum solution; especially when good "off-design" properties are required. /18

This is especially true for the case where aerodynamic performances are required for a given wing planform and a specified lift distribution, which in addition are to bring about a low-weight thickness distribution of the wing. The working range of the wing is then limited by flow separations which can no longer be controlled, or can only be controlled to a limited extent. Large changes in the equilibrium state of the flow forces (inertia forces, friction forces, pressure forces) in the wing boundary layer will start a pressure increase if there are delays in the flow. Using the selected isobar concept, and for a specified wing plan form, we can control the operating limits of the wing in the design stage with consideration of the three dimensional effects during recompression and boundary layer development.

Sudden separation phenomena are undesirable, which are associated with large changes in forces and moments, and will therefore lead to a strong reduction in aircraft stability and controllability. As is well known, the outer wing "tip" region is an especially critical area. It is only possible to influence the separation phenomena during the design in the recompression region of the wing. These can come about, either from a continuous development of the boundary layer or from a shock/boundary layer interaction. The type of boundary layer development over the wing, the development of the pressure distribution as a function of span (first occurrence of shocks, changes in the shocks in the chord /19 direction and physically-possible trailing edge pressure (see Figure 14)) can therefore be directly influenced through the selected design pressure distribution and its characteristic behavior over a specified wing plan form. Wing plan forms of the type of interest here, (commercial or transport aircraft with medium and large aspect ratios) are characterized by a trapezoid plan form with sweepback and a bend in the trailing edge (also leading edge). If one uses the previously-used "straight isobar" concept, which essentially assumes an aerodynamically-representative pressure distribution at the "sheared part" of the wing [8, 11, 27], the aerodynamic limiting load on the wing is then determined by the flow processes along the outer wing. The pressure gradients become more

steep with increasing span in proportion to the change in the chord. There is also an increased tendency for separation in the boundary layer (small local Re-numbers, boundary layer migration). Due to the flow around the wing tip, there is a modification to the isobars at the outer wing. This leads to a flow collapse which is not representative for most of the wing. If one uses the "straight isobar" concept this limiting behavior will, of necessity, be a consequence of the selected design pressure distribution and therefore the expected wing profile (especially thickness distribution), if one conforms with specified operating limits. This then leads to a non-weight-optimized wing profiling. The isobar concept should then be designed so that the special characteristics of the variations of recompression in the span direction are completely exploited in conjunction with the permissible boundary layer load and shock development in order to achieve the operating limits of the wing, and to favorably exploit the thickness characteristics. Measures for influencing the pressure variation /20 in the trailing edge region include the following: adaptation of the $C_{p_{min}}$ [16], setback of the subsonic recompression beginning point, and matching of the trailing edge pressure (downflow angle, cutoff trailing edges, etc.) In order to improve the flow behavior in the region of reduced isobar sweep and to counteract a separation tendency induced by shocks, higher effective design Mach numbers (for shockless recompression) can be used for the profiles, compared to the regions which are not endangered. Figure 15 shows the basic possibilities for building up an isobar distribution matched with a profile plan form. By using the various possibilities for influencing the operational limits, and by exploiting recompression variations, matched to the wing plan form, as well as exploiting the correct set of parameters for the pressure distribution type $(C_{p_{min}}, \frac{x_R}{L}, C_p^*, x_{s1}, x_{s2}, C_{p_{HK}})$, there is sufficient leeway to maximize the thickness over the wing span, and also satisfy the aerodynamic requirements.

3. AERODYNAMIC DESIGN

Satisfactory calculation methods are one of the most important tools for aerodynamic wing design. Also, another important tool is the wind tunnel. The frequency of using these tools during a project

design iteration will point out design uncertainties and gaps.

If calculation methods are not available, which would represent a clear cost savings during the design work, it is recommended to restrict oneself to cost-saving standard methods, or simplified methods. This for the most part will eliminate parameter adjustments which could lead to a falsification of the design result. The calculation methods shown in Figure 16 are adapted to the design of transonically profiled wings. We have checked their forecasting performance using our own tests. We feel that they are satisfactory. Figures 17-21 show the results of our own recalculations. Here we will not give a detailed account of the design cycle and the relationships between computer programs and correction methods. Figure 17-21 shows a "linear" design process. It will be easy to notice the basic ideas. /22

3.1 Design Example

For an actual design case, (Airbus B10) we attempted to use the design concept discussed above. In addition, to the project requirements given in Figure 31, and the design requirements, we wanted to carry out a consequent thickness optimization within the constraints. The profiling of the inner wing was examined with great care and we investigated the contribution of this profiling to the high lift characteristic. Figures 26 and 27 showed the example of a sheared wing profile used here. and gives the results of a thickness/lift optimization.

Because of the fixed wing connection, the shortened air frame and the defined control surface (family concept, commonality), we had to pay especial attention to the minimization of the longitudinal moment. The only solution we could find was a drastic reduction in the "rear loading" of the inner wing and in the wing tip region. The required lift values from the wing profile regions were equalized by higher over-critical contributions on the suction side, and by flattening the profile underside in the nose region (Figure 26). This led to a clear reduction in the longitudinal moment (Figure 28).

Even though we theoretically-determined the required operational limits (boundary of linear lift increase), the outer wing requires improvement in its separation behavior in the range of low design Mach numbers. At high angle of attack angles, a "pitch-up" tendency is

recorded (Figures 29 and 30), which is not desirable. The only re- /23
maining solutions were "Kuechemann-Tips" [11] or a further unloading
of the wing tip from overcritical width contributions (reduction in
width $C_{p_{min}}$, design of a tip profile for even higher Mach numbers).

3.2 Comparison of: B 10 - Design - A 300 B.

Figure 31 shows a planform comparison of the two aircraft, and shows the important design data. Compared with the A 300 B, the B 10 has an increased aspect ratio and a clearly higher lift load.

Figure 32 shows the thickness distributions $((\overline{D/L})_{max}, (\overline{D/L})_{KASTEN})$ [kasten = box] of both aircraft. The B 10 has a thickness of $\overline{D/L} \sim .15$, and this results in a very large improvement (42%), compared with the A 300 B ($\overline{D/L} = .105$). Operating limits can be compared using Figure 33. We find that for about the same standard of the "sheared wing" profile of both aircraft, (Figure 34), substantially higher limiting lift values are achieved for the B 10 in the mission range of interest. This was only possible by using a profiling which is matched with the flow in the span direction, that is, by introducing an isobar concept which is matched to the plan form. Figures 35 and 36 show the theoretical pressure distributions and isobar variations for both wings. From the dashed "critical" isobars (C_p^*), we can see how the "straight isobar" concept was used for the A 300 B, with a substantial overcritical unloading (thickness reductions) of the inner wing (Figure 35). Figure 36, on the other hand, gives the B 10 design, and shows an isobar variation adapted to the wing plan form with a strong overcritical load on the inner wing.

Figures 37-40 show the development of the pressure fields along both wings when approaching the operational limits ($Q^{\uparrow}, M_q^{\uparrow}$). The comparison of the wings was based on comparison of only a few important design characteristics for the high-speed range. We can expect a clear improvement in the sense of higher economy for the "thick" transonic wing.

We assume that the increased design thickness will not only result in more favorable weight characteristics compared with the high-speed design (wing box structure weight, Figure 4), but also by saving the weight of the additional high-lift devices, we will then achieve a "organically"-designed wing (Figure 13).

4. SUMMARY

/25

In an actual design we examine to what extent the use of well-known design concepts could lead to weight-optimum and operating cost optimum solutions, exploiting the possibilities of thick transonic profiles. The usual design criteria concepts used for optimizing the overall function of the wing were considered to be too restricted and not sufficiently appropriate for the physical processes over the wing. Suggestions have been made for improving the situation, and these have been examined on an actual design. Compared to previously designed wings according to conventional criteria, we find that the new design is superior in several aspects. We reached the conclusion that an isobar concept matched to the plan form in conjunction with a "organic" design will lead to a flight profiling resulting in optimum weight characteristics.

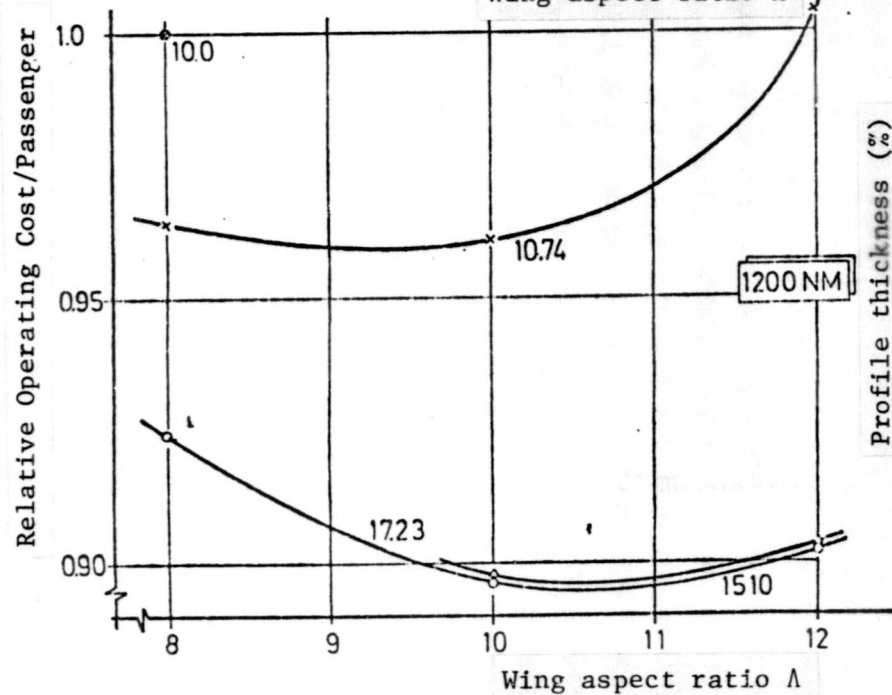
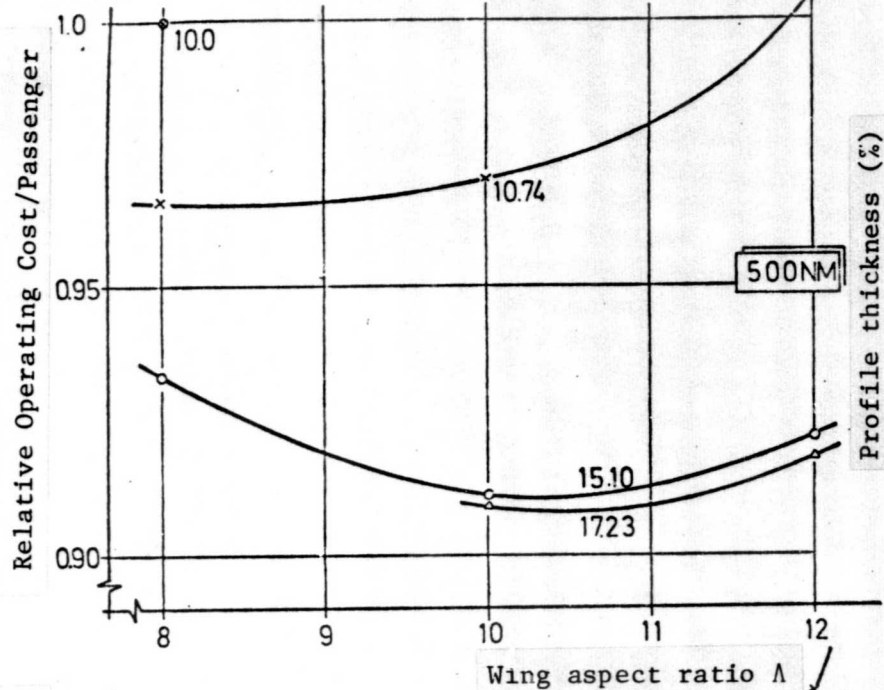
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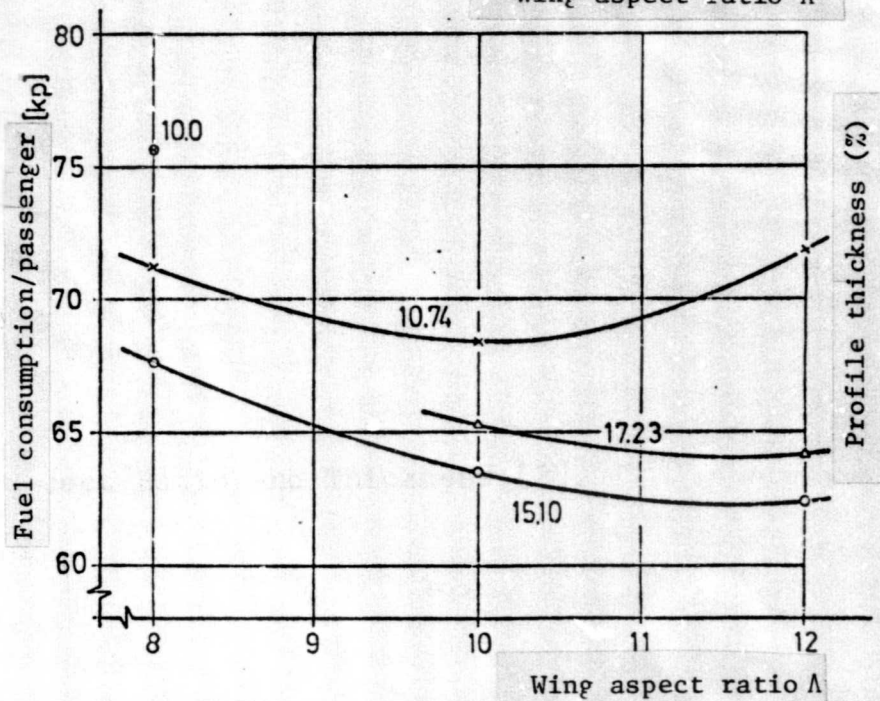
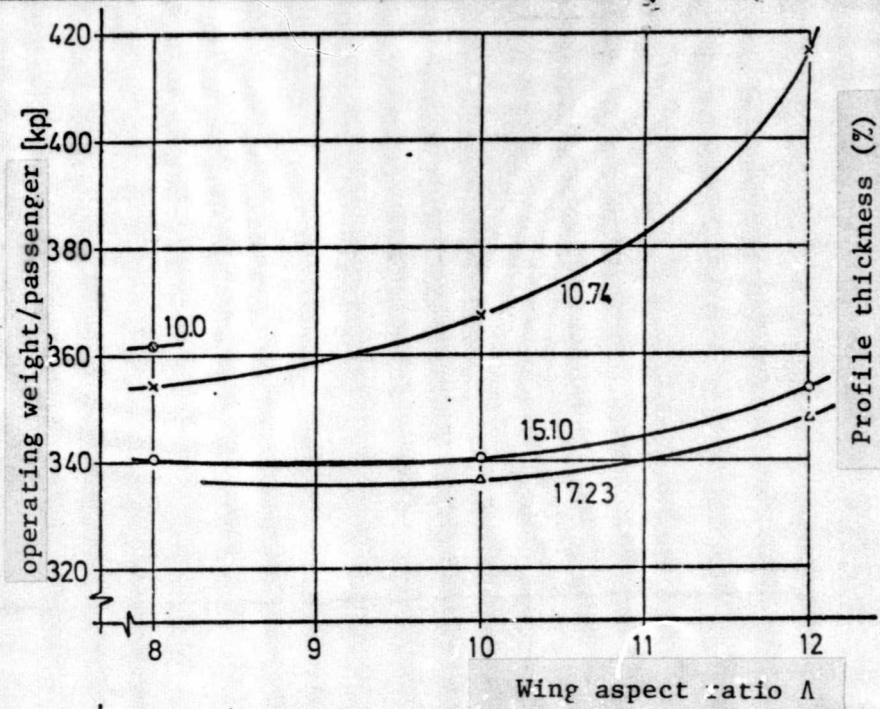
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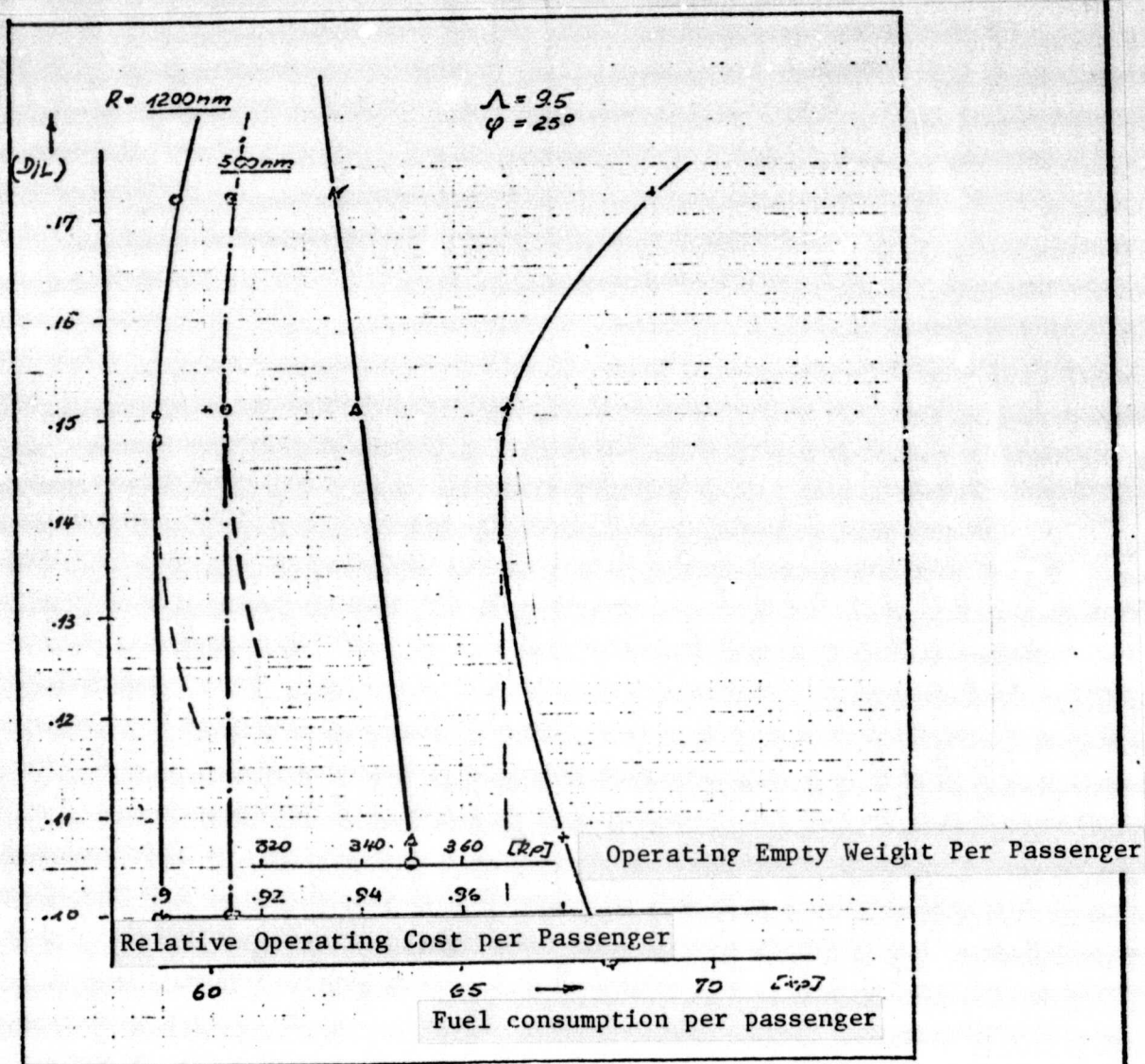


Figure 2: Project Preliminary Optimization. Selection of "Most Economic" Profile Thickness.

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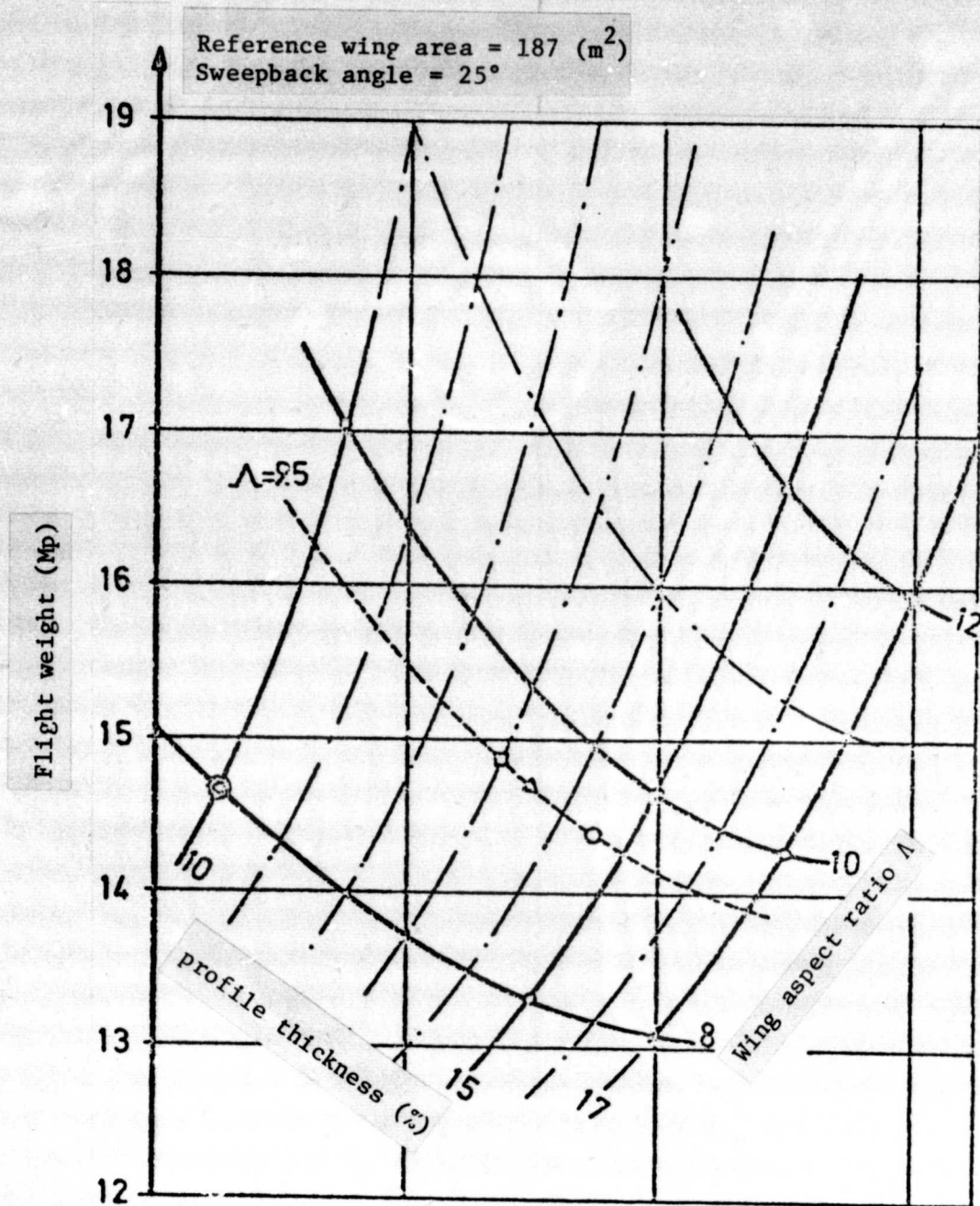


Figure 3: Dependence of Wing Weight on Relative Thickness and Wing Aspect Ratio. [2]

STRUCTURAL ADVANTAGES OF THICK TRANSONIC WINGS

Room for connecting wheels
storing flaps lift

therefore simpler construction
gaining weight

Stiffness increase with height.
more flutter safety margin
reduced bending

Bending stiffness, $E \cdot I_B \sim k \cdot H^2$

Torsion stiffness, $k \cdot H < G \cdot I_T < k \cdot H^2$

H = average spar box
height

Weight-Saving with Height

Greater aspect ratio without
additional weight

wing (210m ²)	Λ	δ	flight weight	
			kp	(%)
B10X-2	9,5	13,85	16100	100
B10X-2 thin	9,5	10,5	17400	108
B10X-2 thick	9,5	15,0	15660	97
A300 scaled	8,0	10,5	16100	100

structure including central tank in fuselage

Figure 4: Results of a structural investigation of the transonically profiled wing with large aspect ratio [4].

RELATIVE THICKNESS DISTRIBUTION

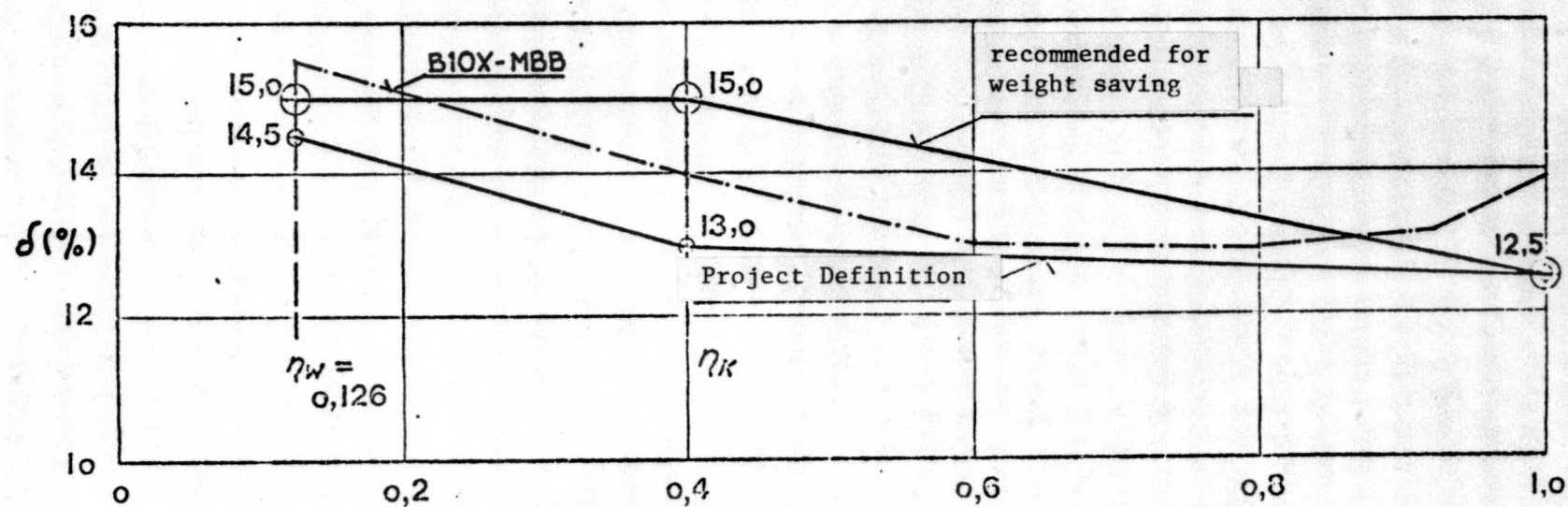


Figure 5: Preliminary Design of the Limitations on Wing Thicknesses

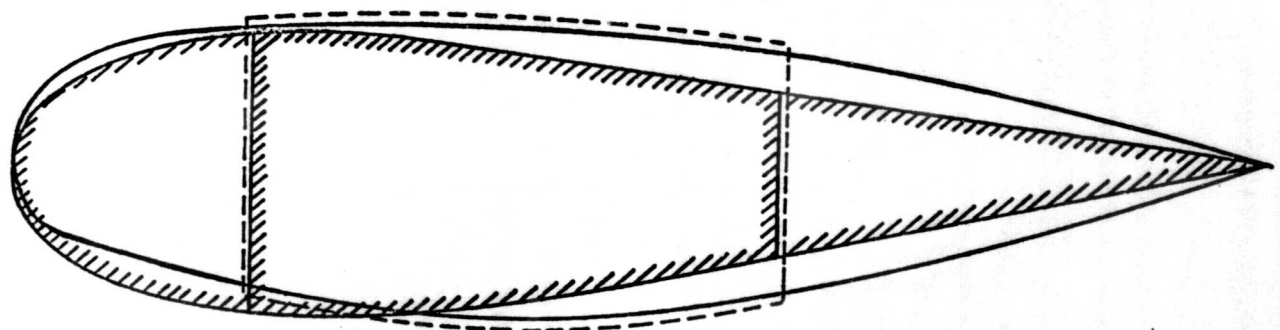


Figure 6: Explanation of the Structural Exploitation of the Box Region from Profiles having equal thickness.

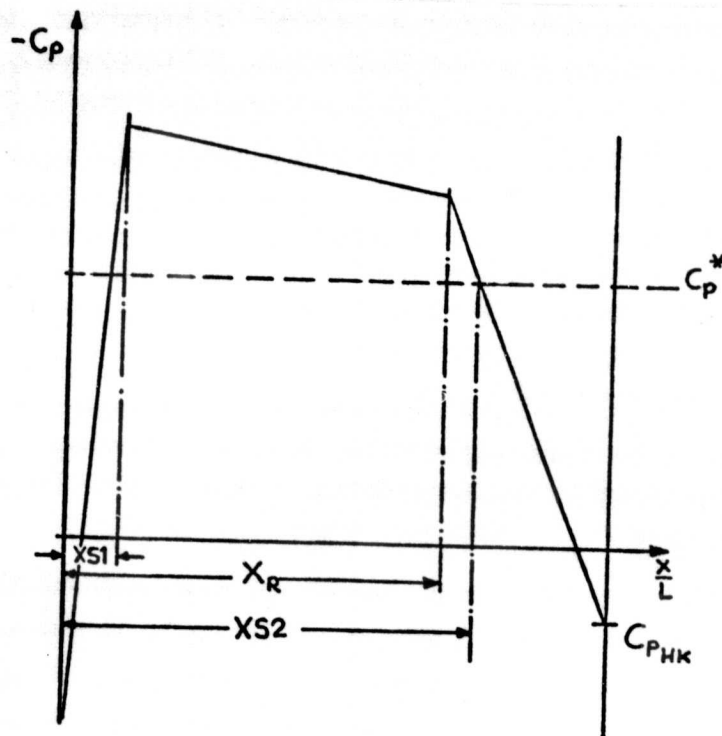


Figure 7: Simplified Description of a Transonic Pressure Distribution

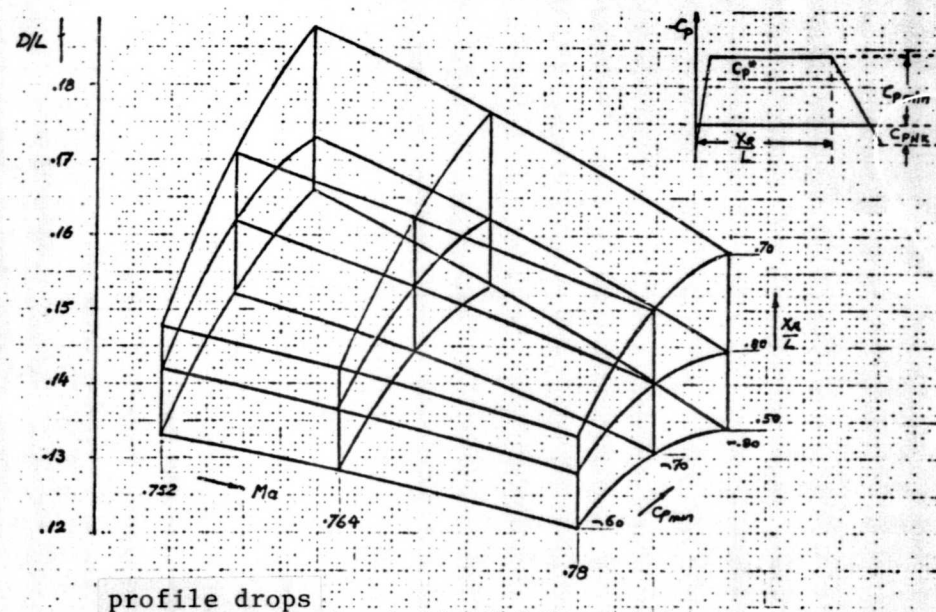
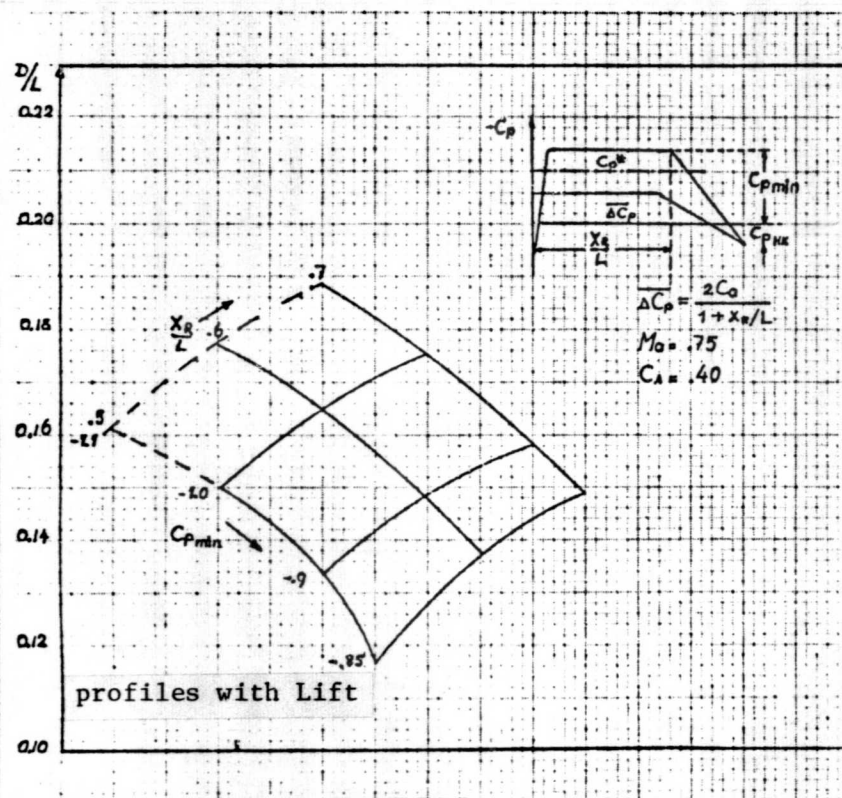


Figure 8: Influencing the Thickness Distribution of Transonic Profiles Using Pressure Distribution Parameters [13, 14].

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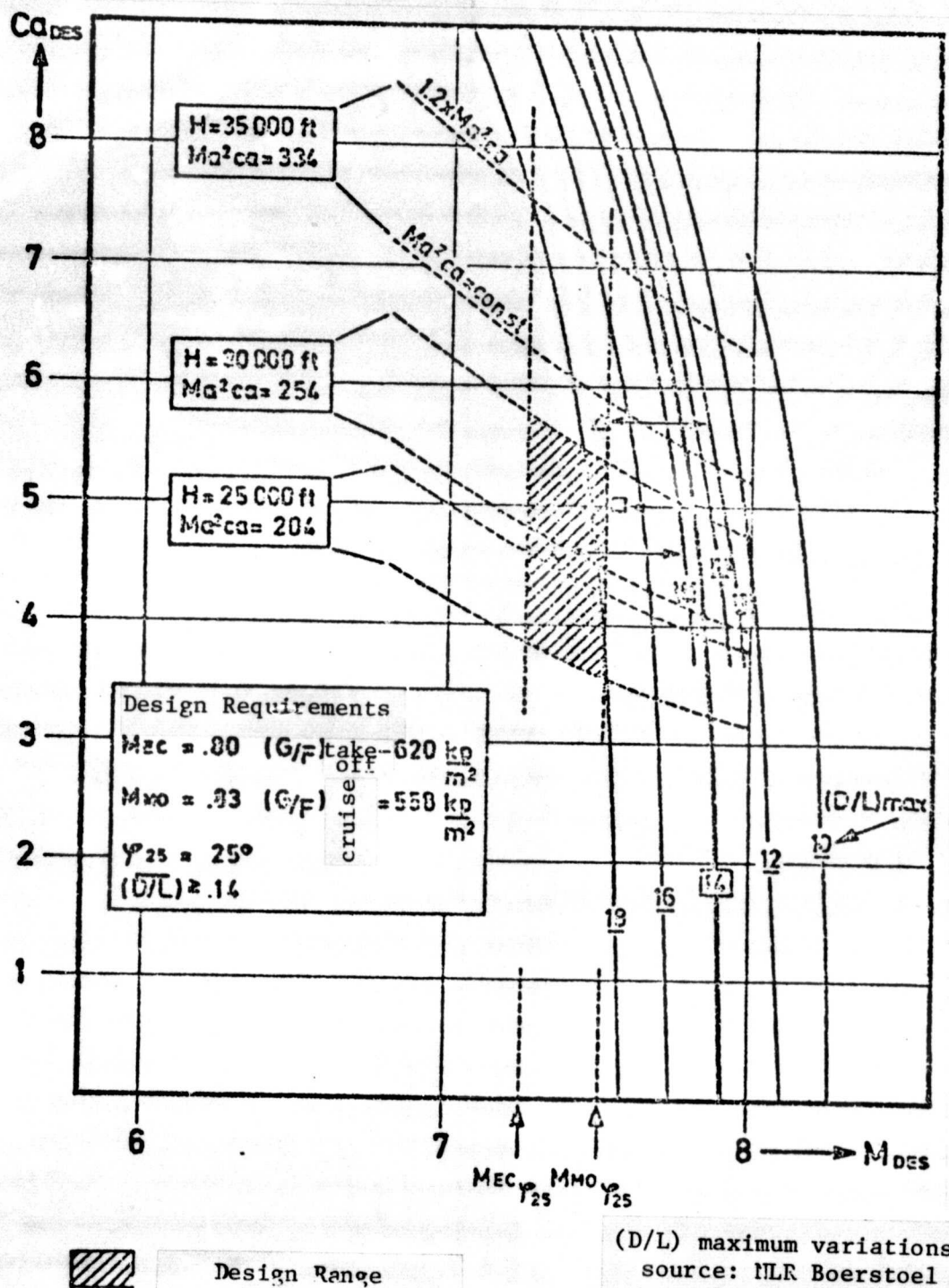
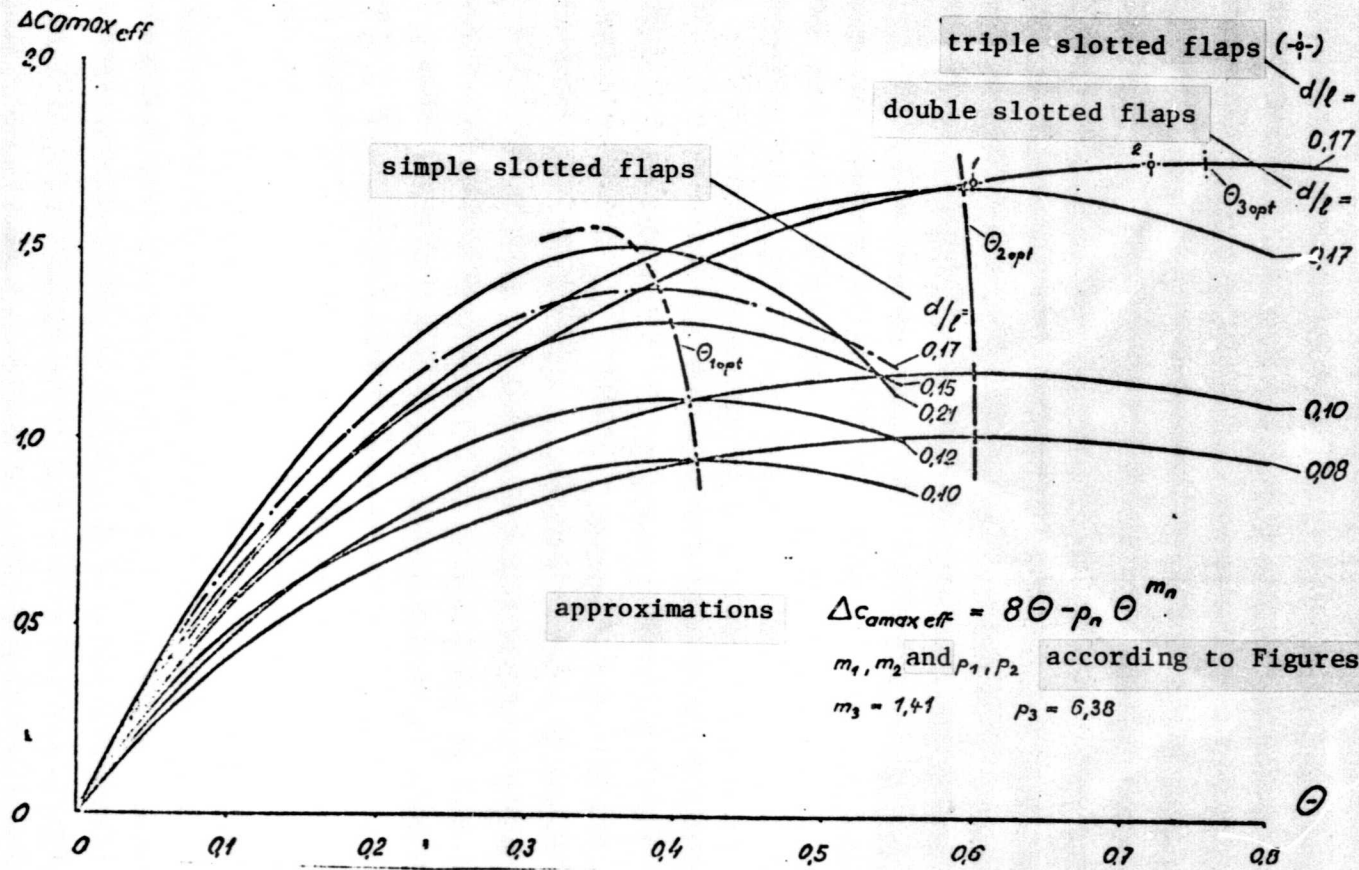


Figure 9: Lift/Thickness Limits of Transonic Profiles According to Boerstool [15].



θ = rough geometry parameter of flap system

$$\theta_n = \sum_{i=1}^n \eta_{ki} \sqrt{\frac{l_{ki} + l_{ki+1} + \dots + l_{kn}}{l_{eff}}}$$

Figure 10: Limiting Lift Values of Slotted Flap Systems. Dependence of Fast Flight Profile thickness and Usable Additional Lift Brought about by Flaps [18].

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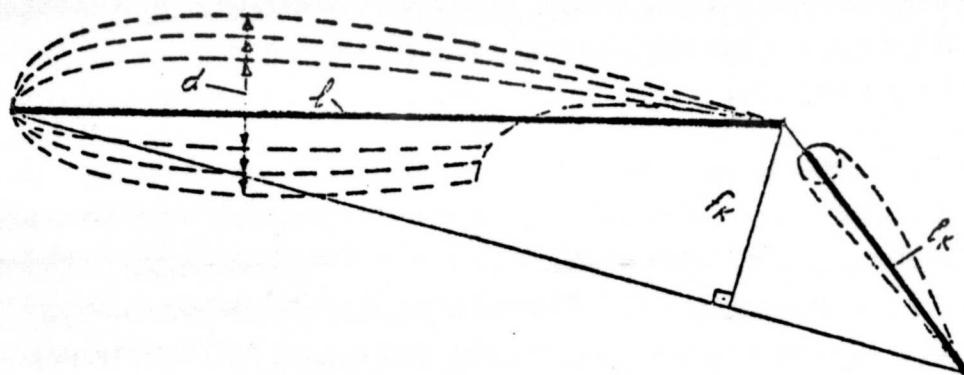


Figure 11: Explanation of the Various Topside Curvature Component of the Flap Wing System, Main wing-simple slotted flap [18].

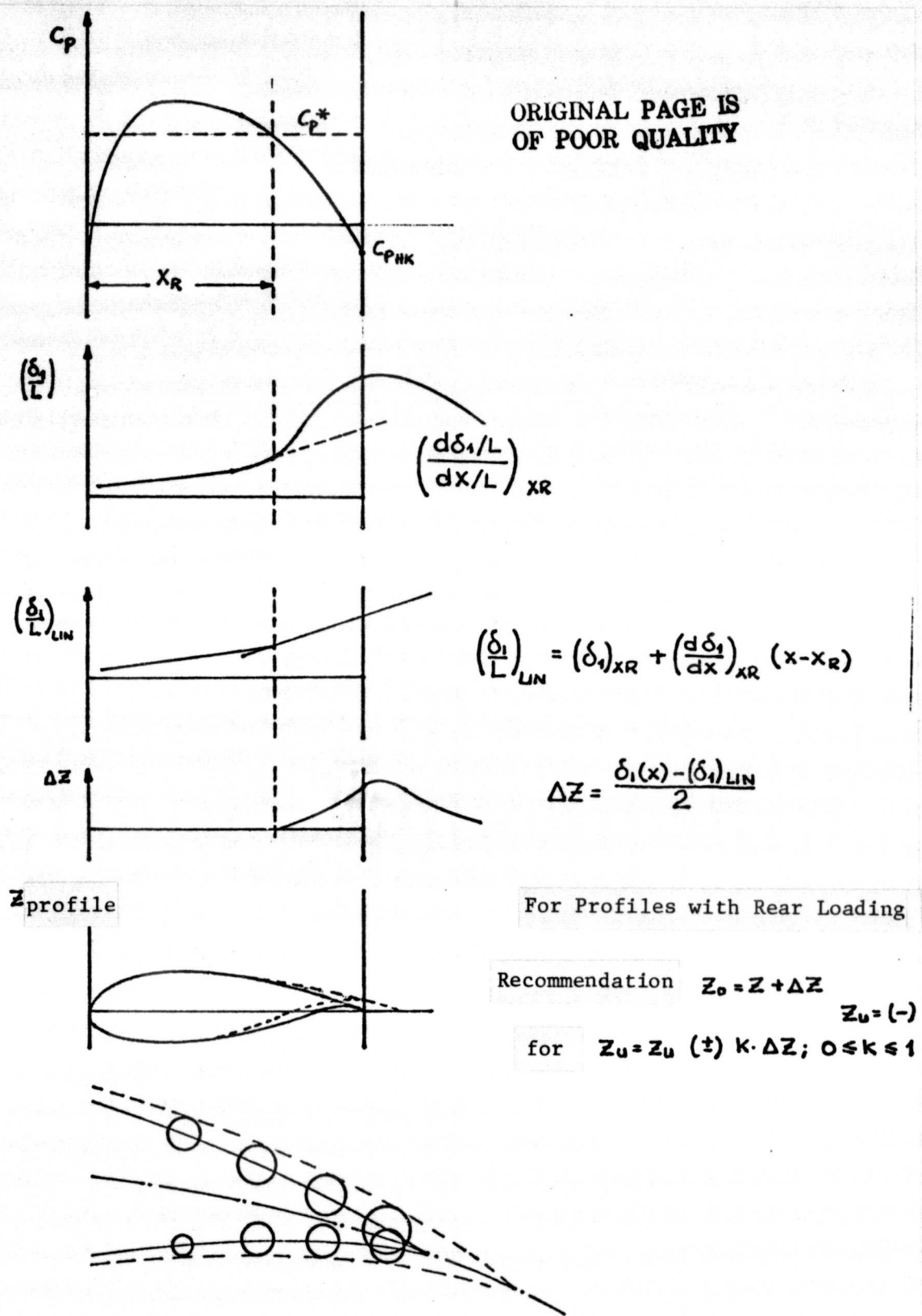
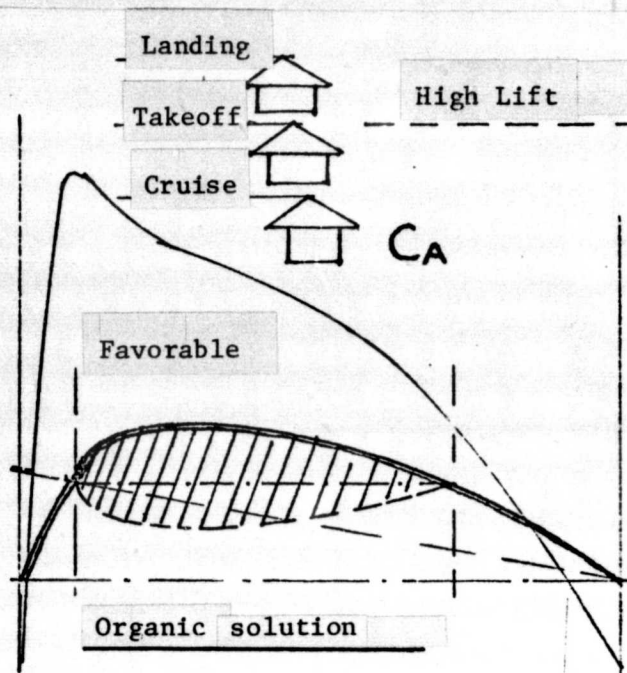
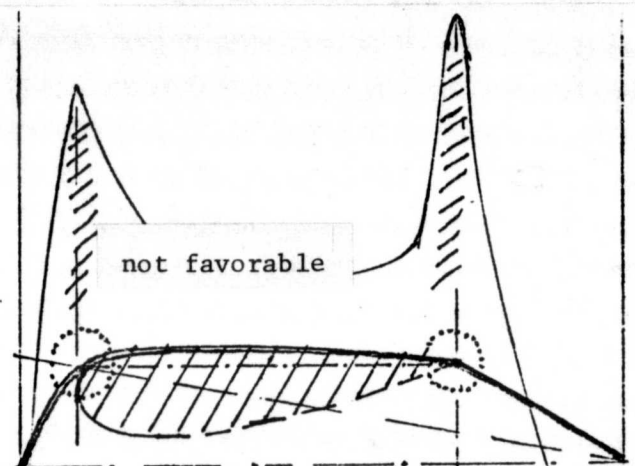


Figure 12: Measures for Influencing Recompression Variations.



"Organic" Development of the High-Lift Skeleton from the "Topside" Curvature of the Fast Flight Profile.

EXPECTED: LARGE SUCTION SIDE LIFT. AERODYNAMICALLY-EFFECTIVE HIGH LIFT SKELETON. FAVORABLE FLOW SEPARATION. LARGE HEIGHT CONTROLLABLE LONGITUDINAL MOMENT. REDUCED LIFT LOSSES. OVERALL: HIGH EFFECTIVE GLIDE COEFFICIENT.



LOW SUCTION SIDE LIFT. POOR CONTOUR TRANSITIONS TO THE HIGH LIFT SKELETON. THIS CAUSES FLOW LOSSES, INCREASED COMPLEXITY OF HIGH LIFT AIDS, LONGITUDINAL MOMENTS DIFFICULT TO CONTROL. LIFT LOSSES. OVERALL: LOW EFFECTIVE GLIDE COEFFICIENT

"additive" solution:
fast flight profile
+ flap wing
+ optimum installation losses

$$\frac{A_{eff}}{W} \approx \frac{C_A - \Delta C_A \text{ added weight}}{C_{WR} (1 + K_0 \cdot D/L) + K_1(C_A + \Delta C_A) + K_2(C_A + \Delta C_A)^2}$$

Figure 13: Explanation of a "organically"-designed wing profile.

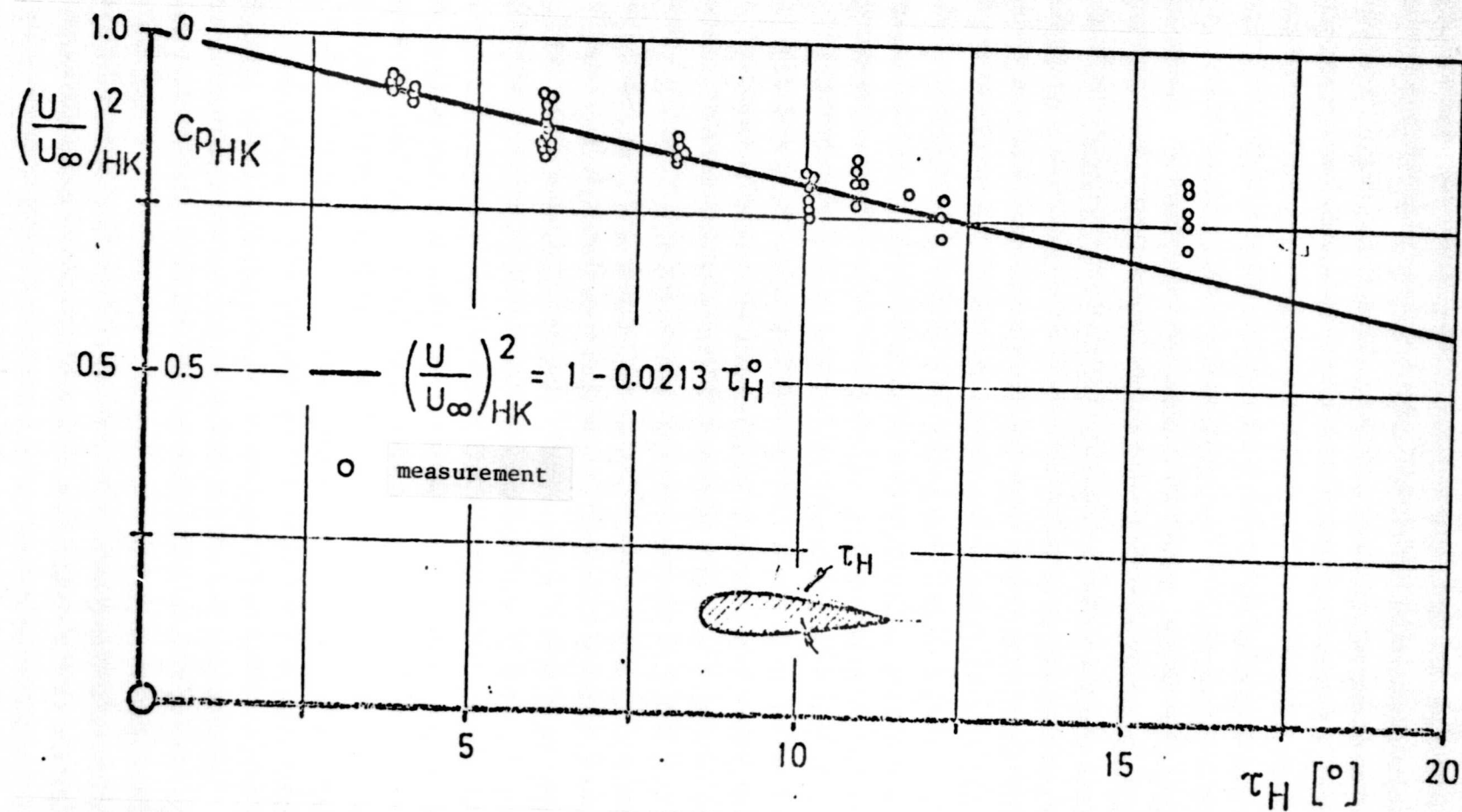
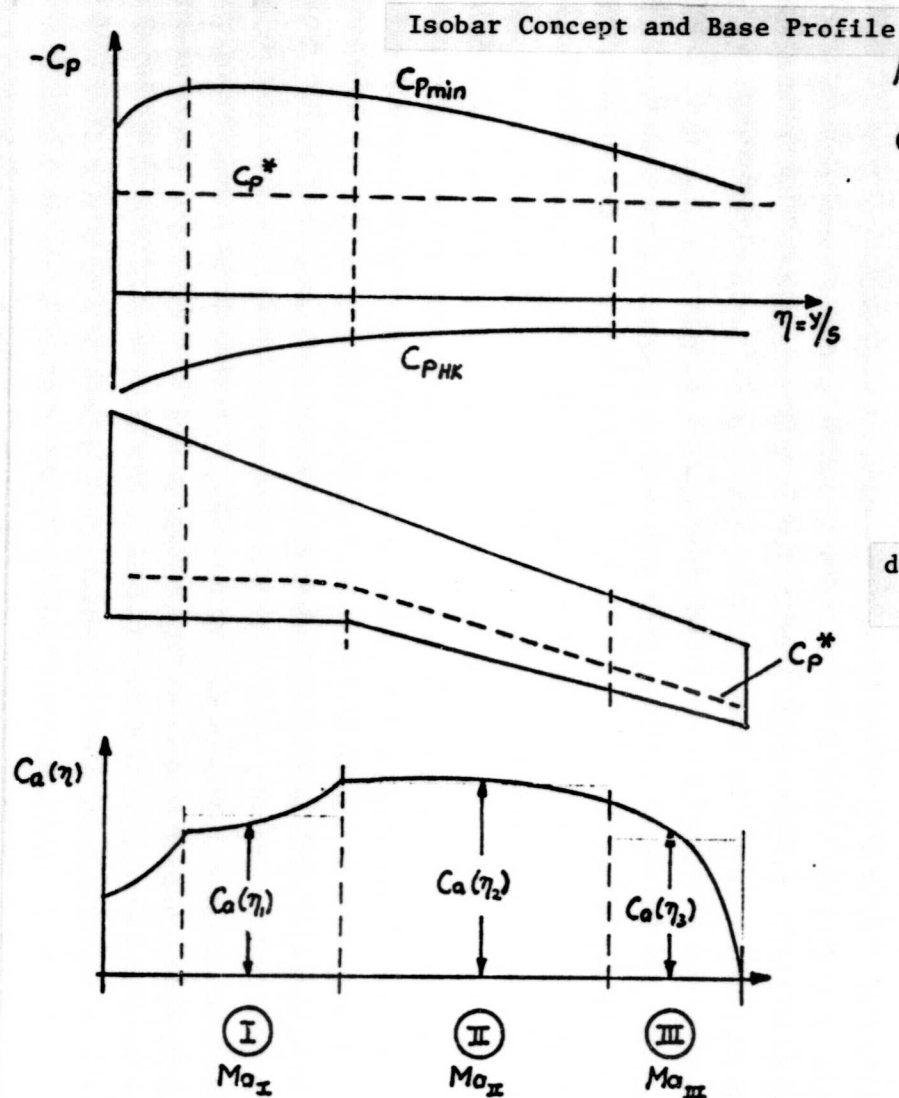


Figure 14: Dependence between Trailing Edge Pressure and Trailing Edge Angle, According to Gruschwitz [28].



design of base profile using transonic theory [23, 24, 25, 26, etc.]

SIDE CONDITION:
"GENTLE" SHOCK DEVELOPMENT
DESIGN SUITABLE FOR THE MISSION
 $M_{DESIGN} \sim M_C$

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Figure 15: Isobar Concept Matched to the Plan Form and Design of Base Profiles.

Figure 16

SUMMARY OF CALCULATION METHODS

SUBSONIC VERSIONS		TRANSONIC VERSIONS		BOUNDARY LAYER SIMPLIFICATIONS
Design	Postcalculation	Design	Postcalculations	
Weber method. "Semiinverse panel method"	Weber method compressible with boundary layer.	Hodograph method, according to Eberle	Garabedian/Korn method, DFVLR version.	Integral method. Walz II in the Thiede/Otte version.
	Panel method. Multibody configuration	Transonic, subsonic, analogy with iteration control using transonic differential method	Difference method according to Murman/Krupp coupled with G. S. and coupled subsonic approximate calculation for influence of thickness and starting solution.	Compressible, laminar, and turbulent boundary layer. Extension beyond separation point for simulating weight with simple semiempirical relationship for turbulent boundary layer $c_f = 0$.
3-D	Extended wing theory (vortex-lattice) fuselage influence according to Koerner and (unknown)	Reversal of design with fuselage and engine fairing	Subsonic analogy method Iteration coupling of subsonic design and design transonic postcalculation method with checking of boundary layer development.	Transonic difference method (small distributions). Expansion of the program version of Dornier.
				Integral method according to Cumpsty-Head. Compressible version acc. to Redeker turbine, compressible boundary layer up to separation point, varied extension to wings in sense of a simple strip method (consideration of average span - dependent isobar sweep and wing chord).

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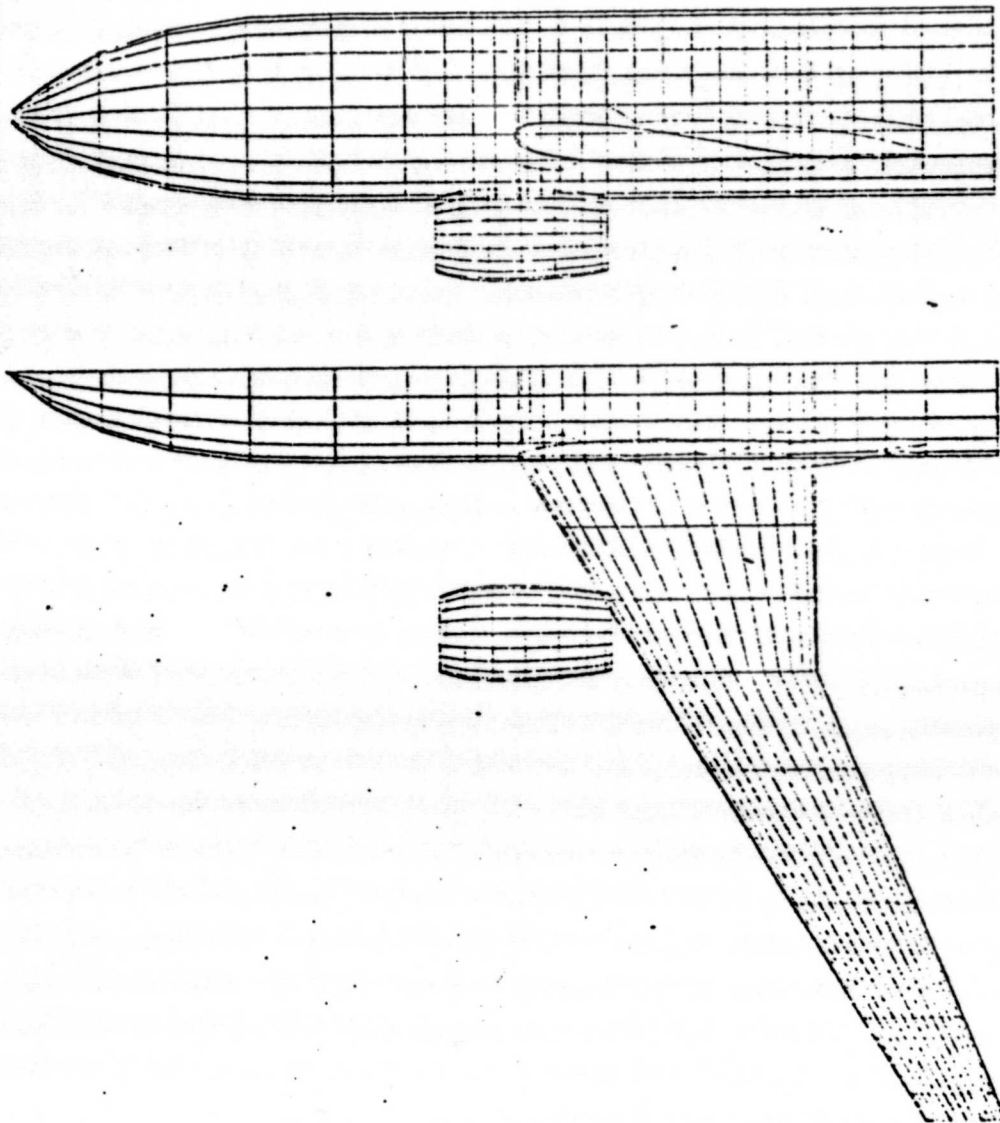
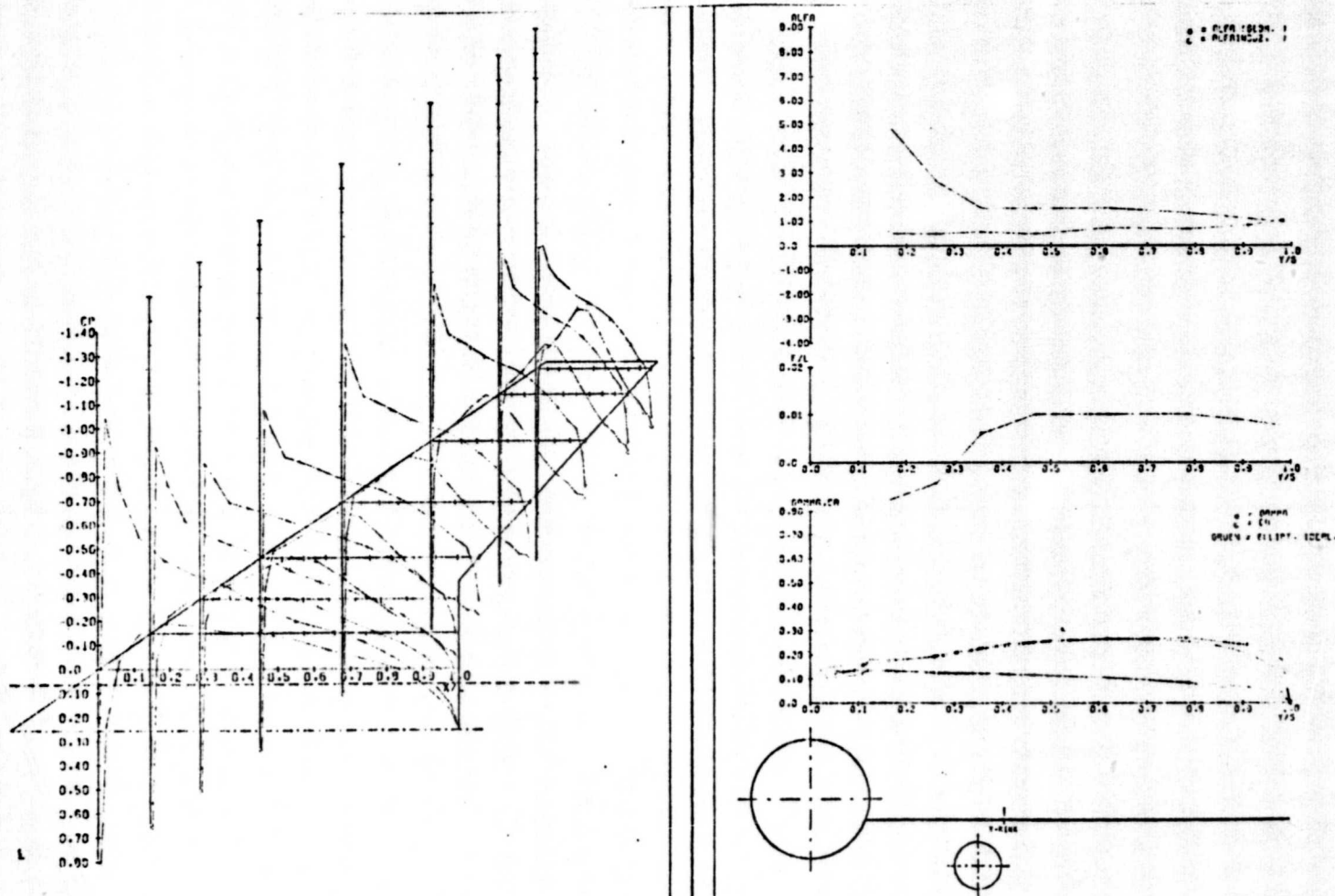


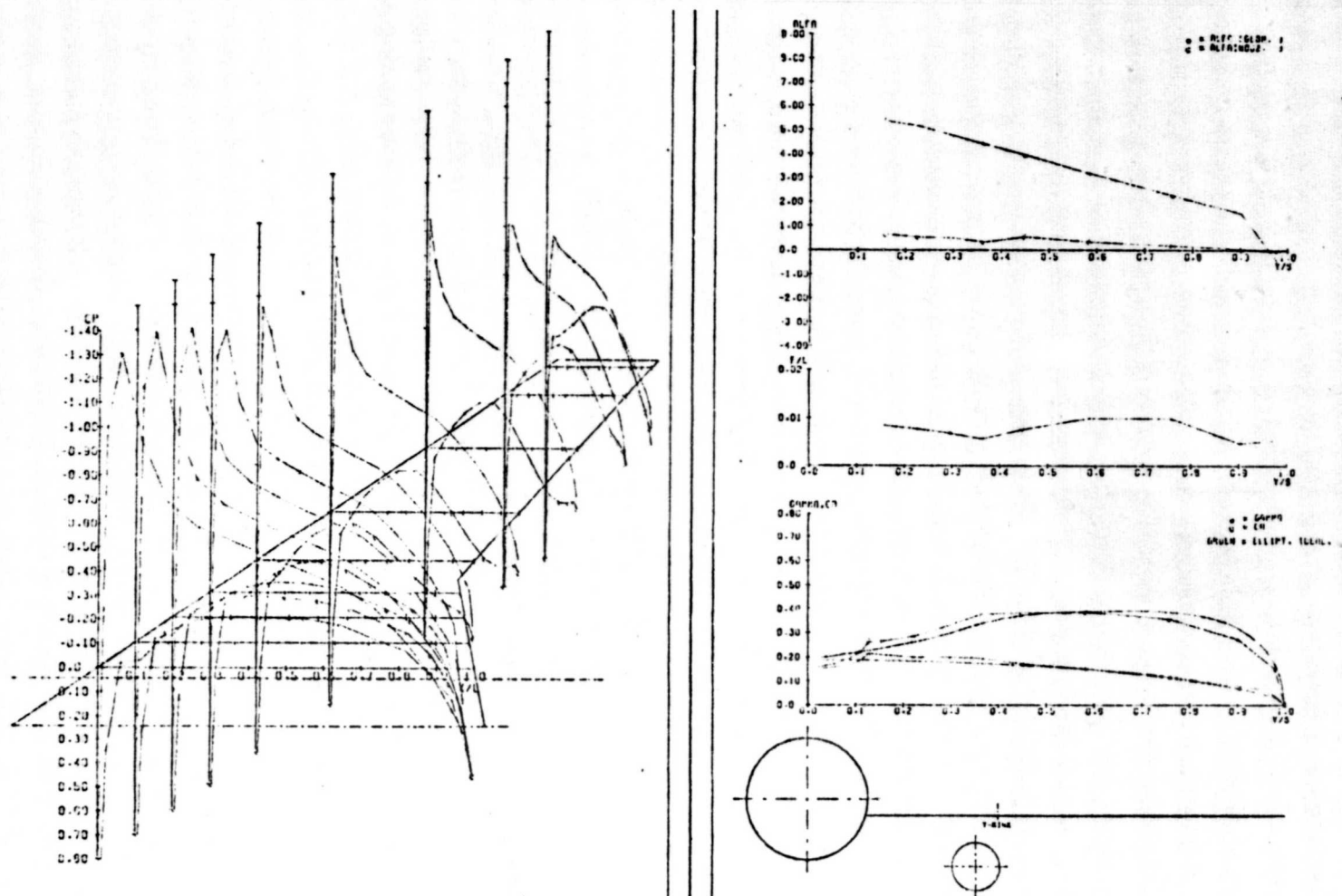
Figure 17: Example of surface discretization for the design and post-calculation according to [30, 31].



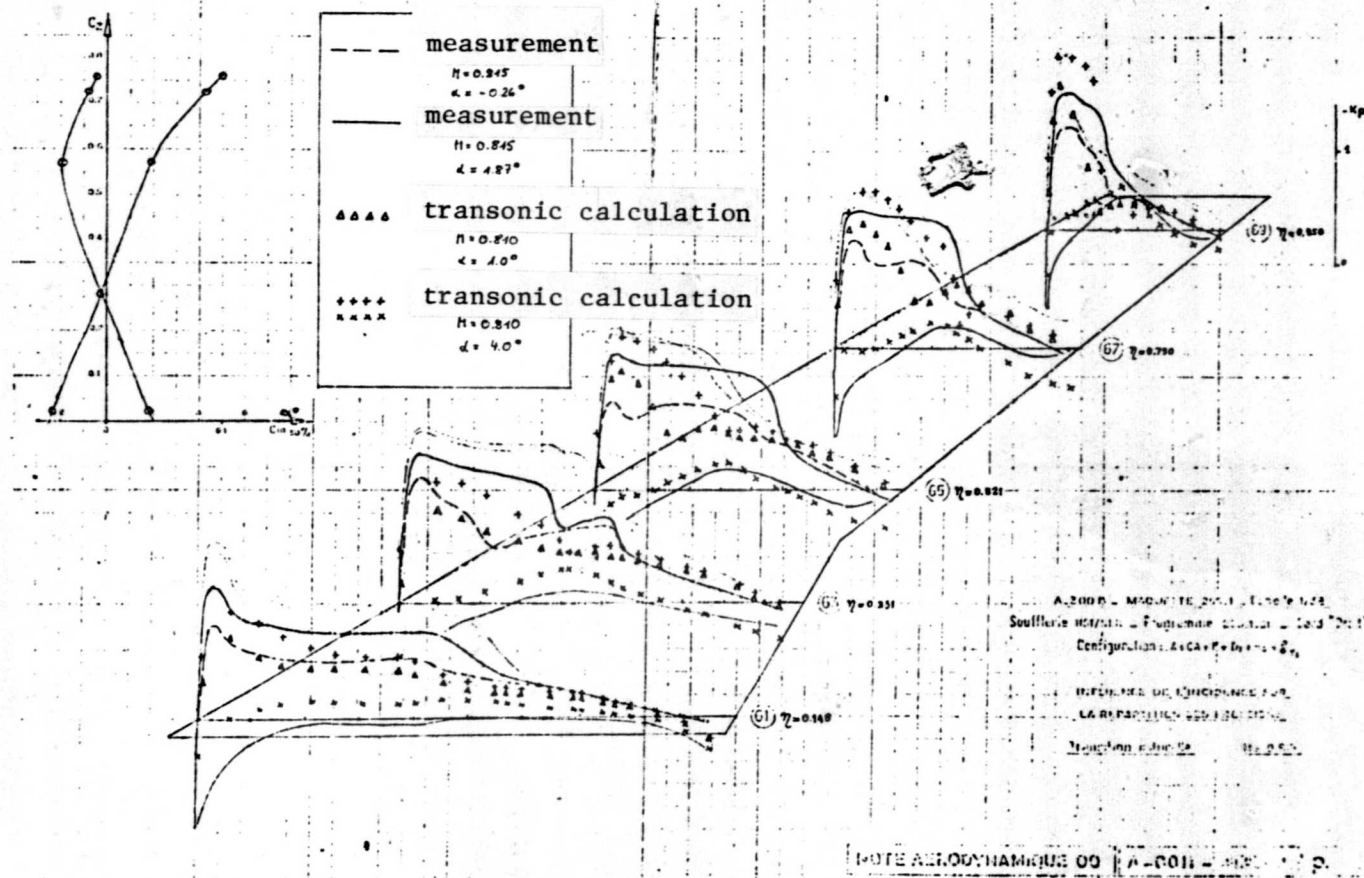
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Figure 18: Results of a subsonic post calculation (linear theory, [29]) for the A 300 B [30].

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30 Figure 19: Results of a subsonic design and postcalculation (linear theory) for a B 10 X [30].

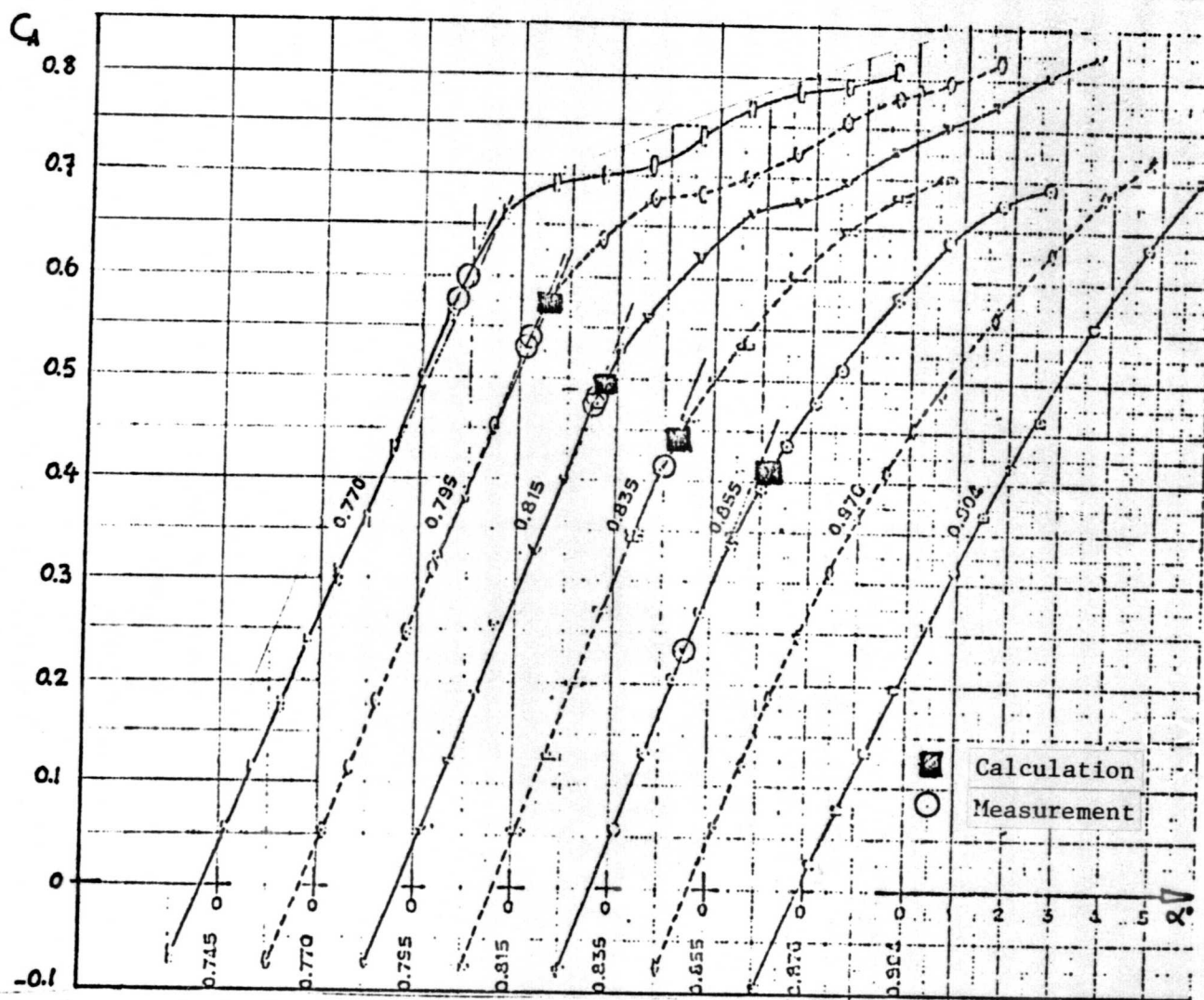


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Figure 20: Comparison of transonic postcalculation and measurement results for the A 300 B [HST/NLR].

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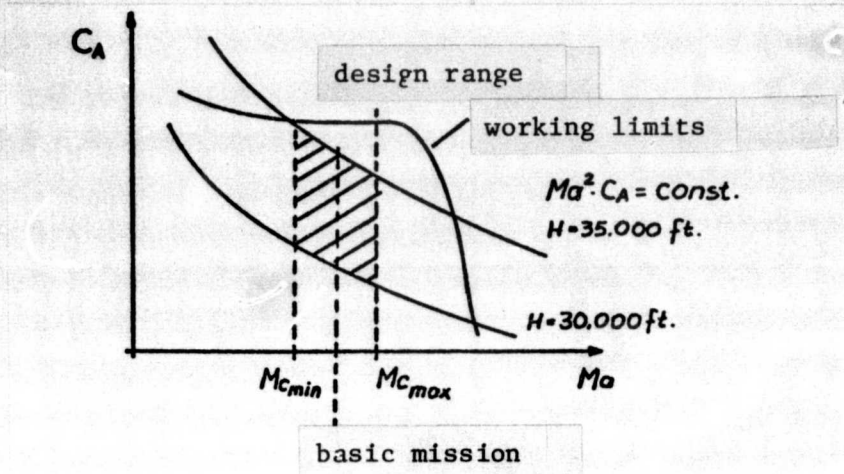


Aerodynamic Note A-0011-50.11/1/36

41 Figure 21: Comparison of theoretical and experimental linearity boundary for the A 300 B.

DESIGN PROCEDURE

PROJECT REQUIREMENTS



M_{MC} , M_C , M_{MO}

G/F_{START} , G_R/F

Λ, λ, ψ , Wing plan form; D/L_{MIN}

Engine position, fuselage geometry D_R , L_R

Required Fuel Tank Volume

Required Design Volume (fuel tank, landing gear, etc)

SELECTION OF BASIC PRESSURE DISTRIBUTIONS FOR TOPSIDE ISOBARS

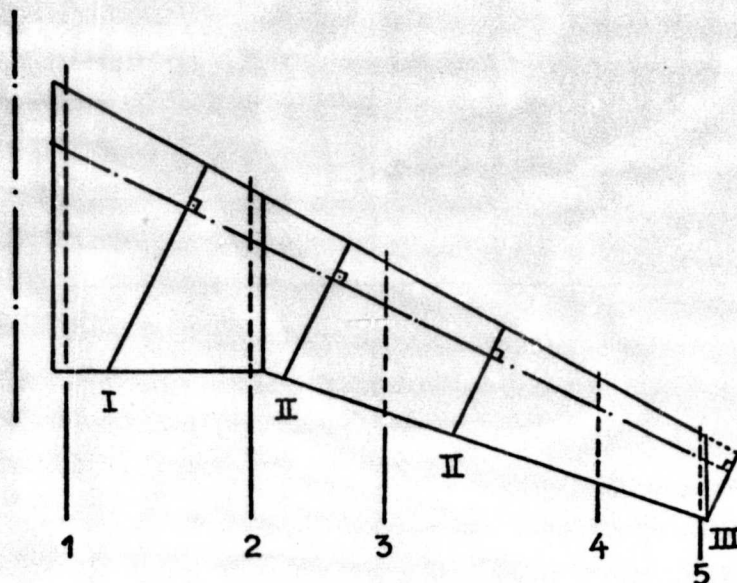
SELECTION CRITERIA FOR: MAXIMUM THICKNESS
TOP SIDE CURVATURE
TRANSONIC OPERATION
TENDENCY TO SEPARATE AS A FUNCTION OF SPAN
LOW SPEED
HIGH SPEED

Figure 22: Design Procedure - Step 1

DESIGN PRESSURE DISTRIBUTION

SUBSONIC ANALOGY: OVERCRITICAL

WORKING WINGS CAN BE DEVELOPED LINEARLY FROM PROFILE FLOWS, JUST LIKE WINGS IN PURE SUBSONIC FLOW



I - III BASE PROFILES
I - 5 Design Steps

INSTALLATION OF BASE PROFILES INTO THE WING CROSS-SECTION
LINEAR STRAKE AND INTERPOLATION OF SECTIONS PARALLEL TO THE FLOW

POST CALCULATION OF THIS WING WITH SPECIFIED TWIST FOR DETERMINING THE DESIGN PRESSURE DISTRIBUTION

SPECIFICATION OF THE TOP SIDE GEOMETRY AND THE WING SECTIONS IN SPECIFIED CONTROL SEGMENTS.

$Z_0(x, \eta)$ FIXED

Figure 23: Design Procedure - Step II.

DESIGN CALCULATION WITH A METHOD EQUIVALENT THEORETICALLY AND NUMERICALLY TO THE POST CALCULATION.

TWIST $\alpha_v(\eta)$

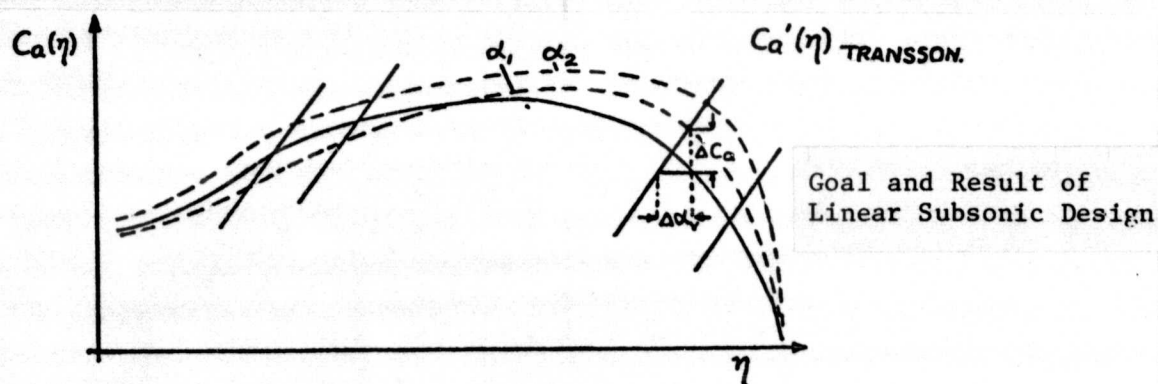
CURVATURE $Z_s(x, \eta)$

DEFINITION OF WING UNDERSIDE

$$Z_u(x, \eta) = -Z_o(x, \eta) + 2 Z_s(x, \eta)$$

TRANSONIC POSTCALCULATION OF THE GEOMETRY FOUND

TEST OF THE DESIGN GOALS. POST CORRECTION

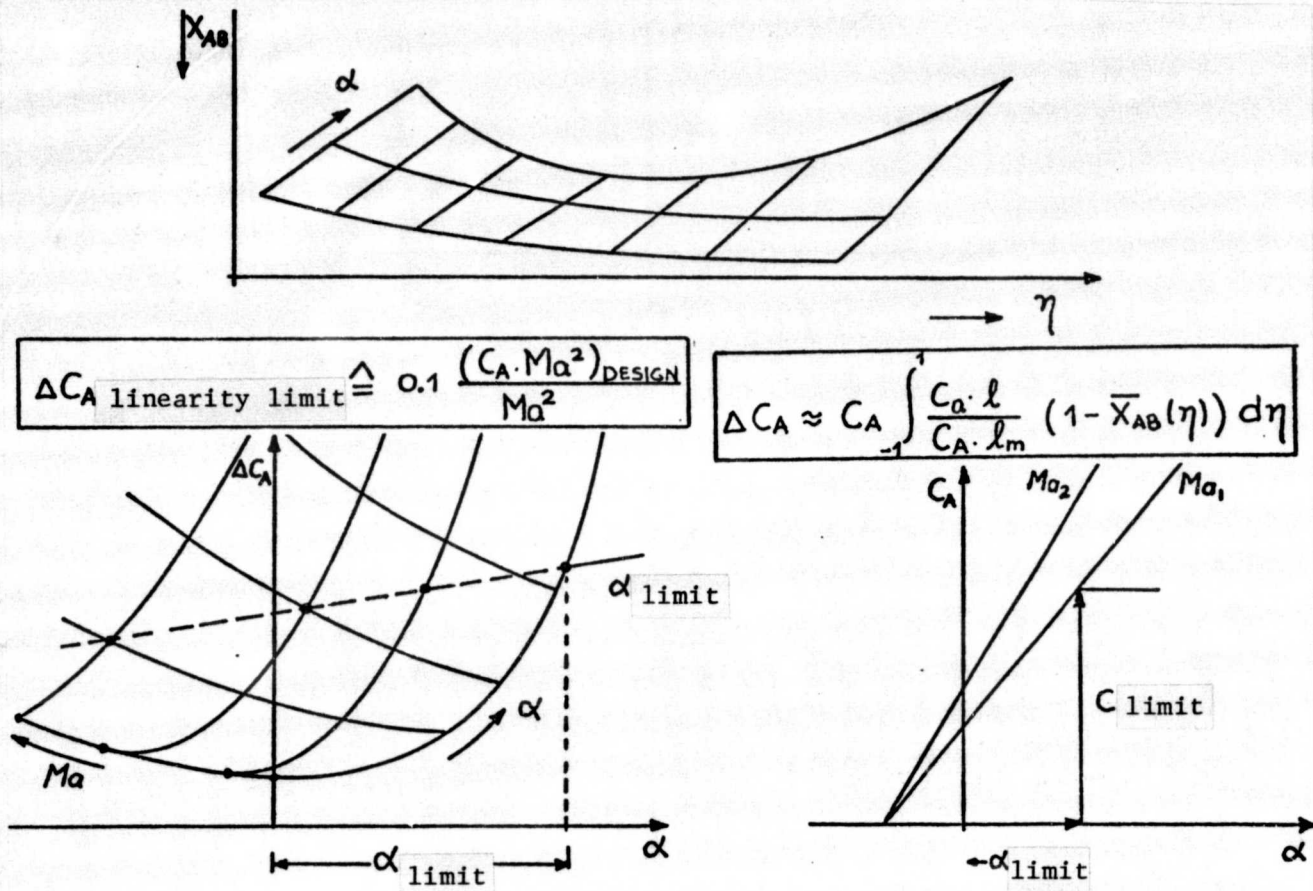


POST CORRECTION OF THE TWIST DISTRIBUTION OF USING LOCAL LIFT INCREASES FOR THE TRANSONIC CALCULATION.

Figure 24: Design Procedure - Step III

CHECKING AND DESIGN CORRECTIONS FOR "OFF-DESIGN" REQUIREMENTS

TRANSONIC POSTCALCULATIONS PLUS BOUNDARY LAYER METHOD, THEORY OF
DETERMINATION OF SEPARATION CHARACTERISTICS AND OPERATING LIMITS



PROCEDURE FOR POST CORRECTION, IF NECESSARY - SEE FIGURE [12]

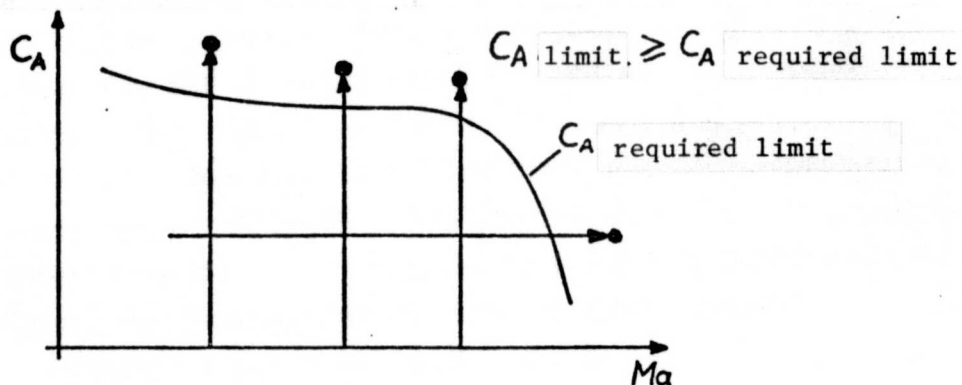


Figure 25: Design Procedure - Step IV

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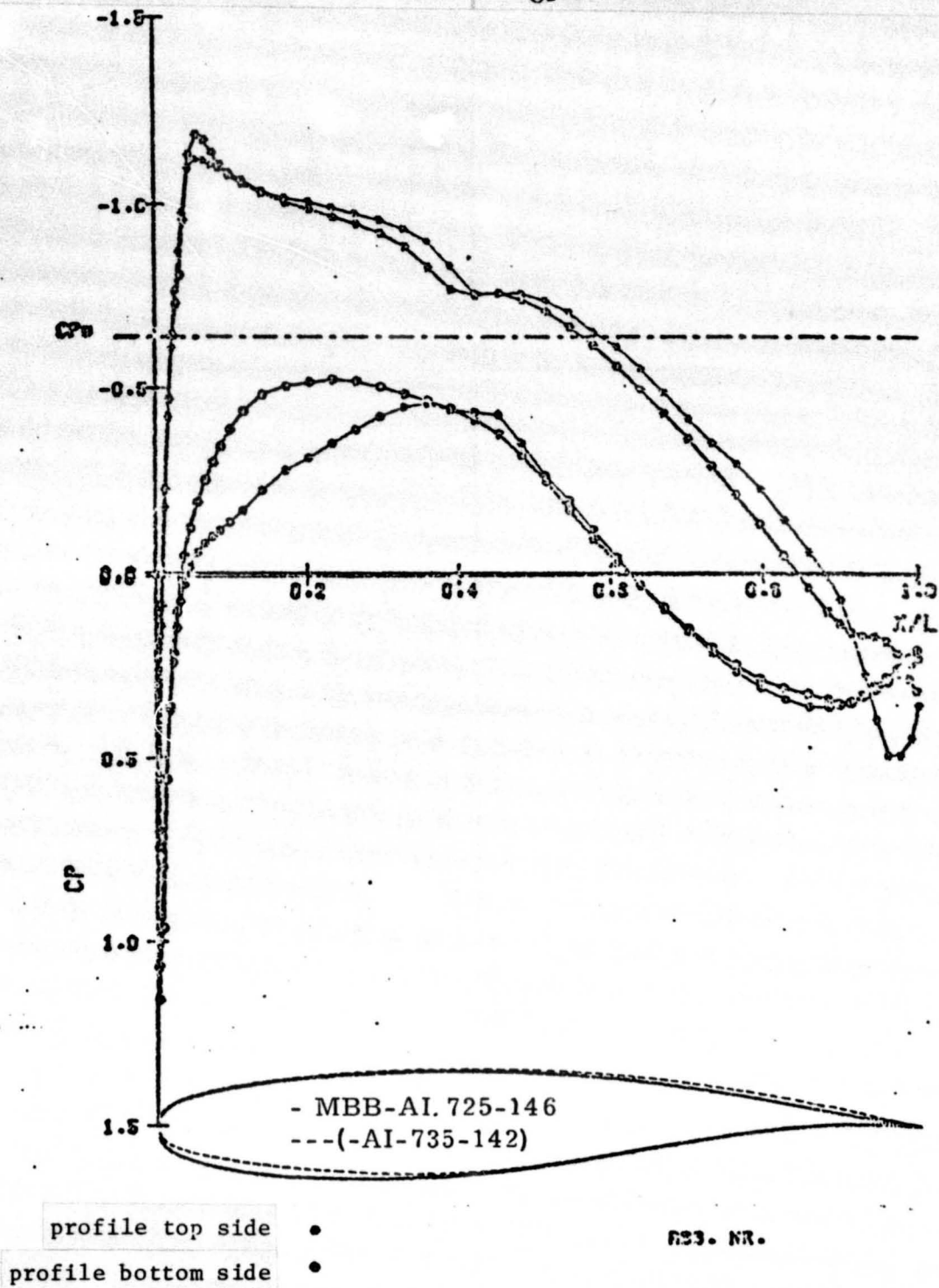
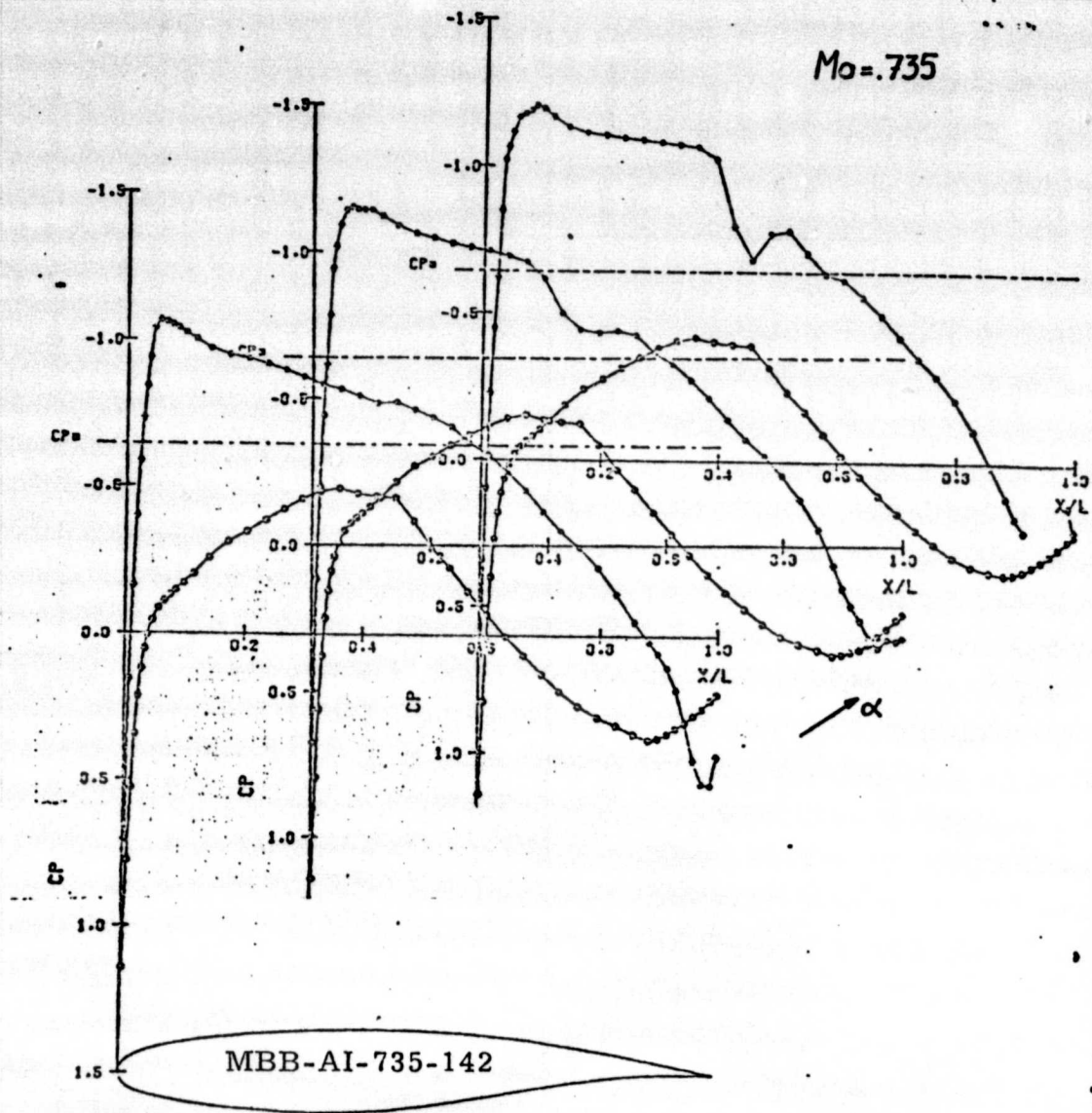


Figure 26: Result of a "Profile Optimization" ("Sheared-Wing" Profile).

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profile top side •
profile bottom side •

APP. NR.

Figure 27: Development of the Shock Position for "Off Design"

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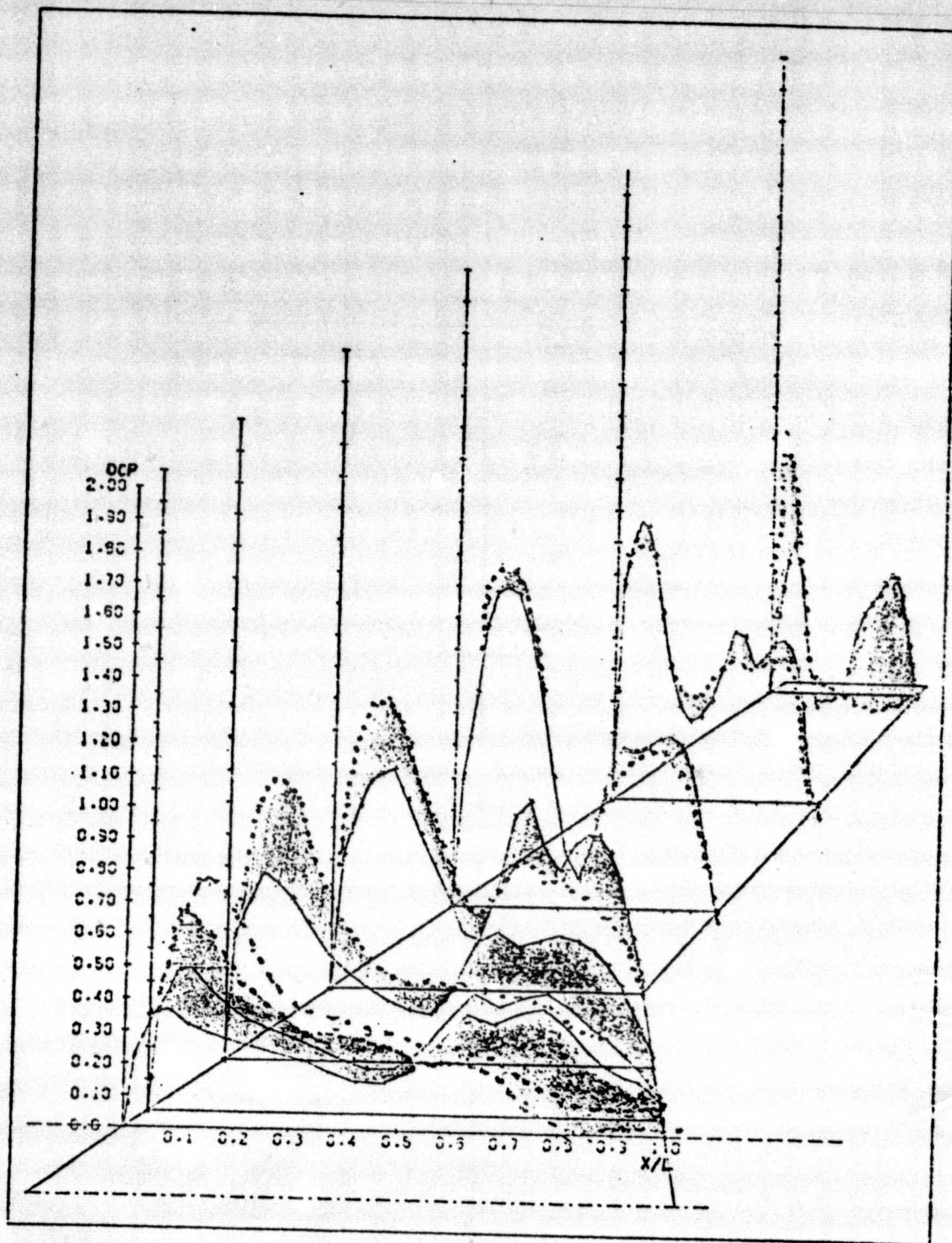


Figure 28: Reconfiguring of the Differential Pressure Distribution for Minimizing the Moment of the B 10 X Preliminary Design

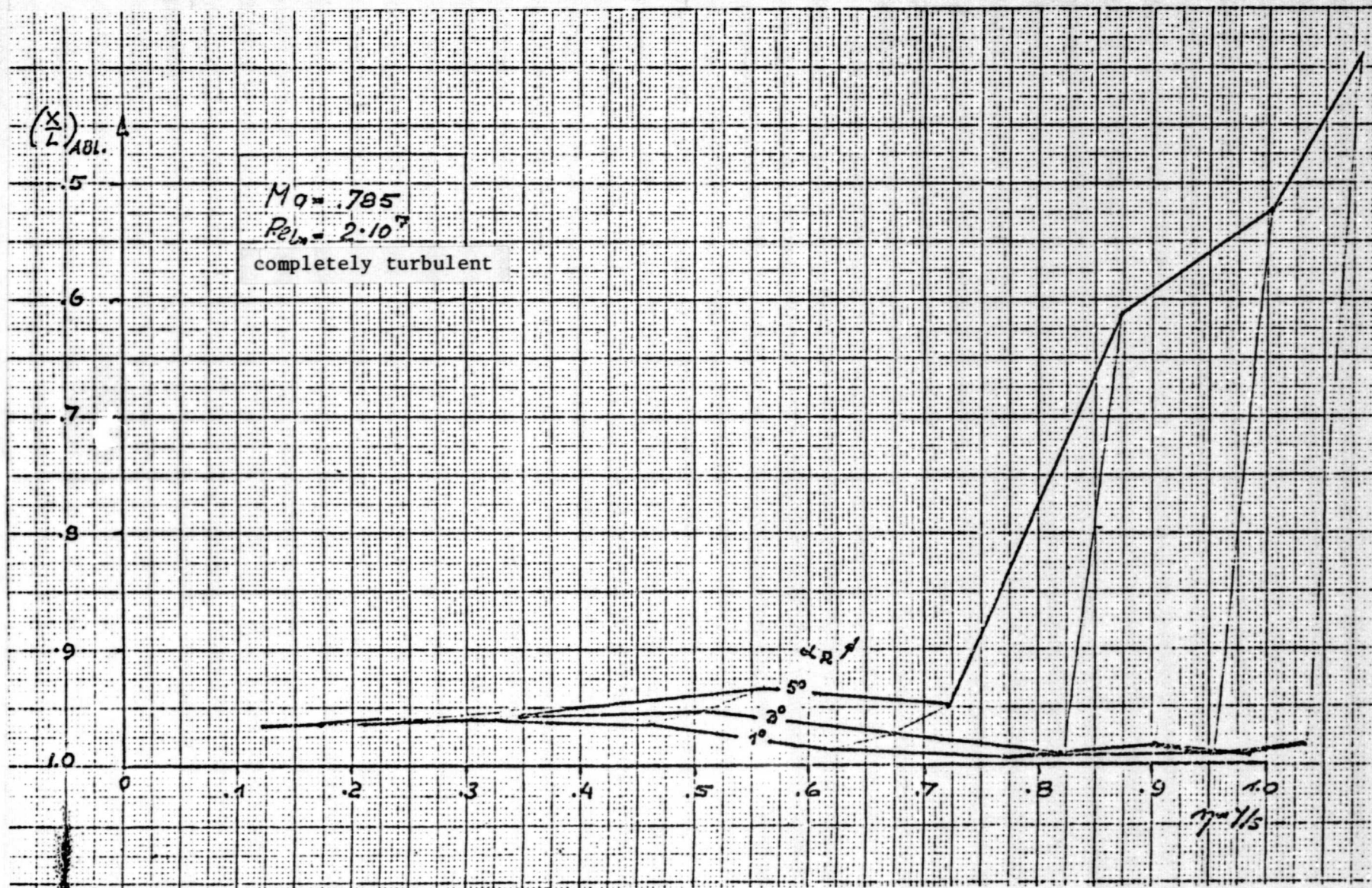
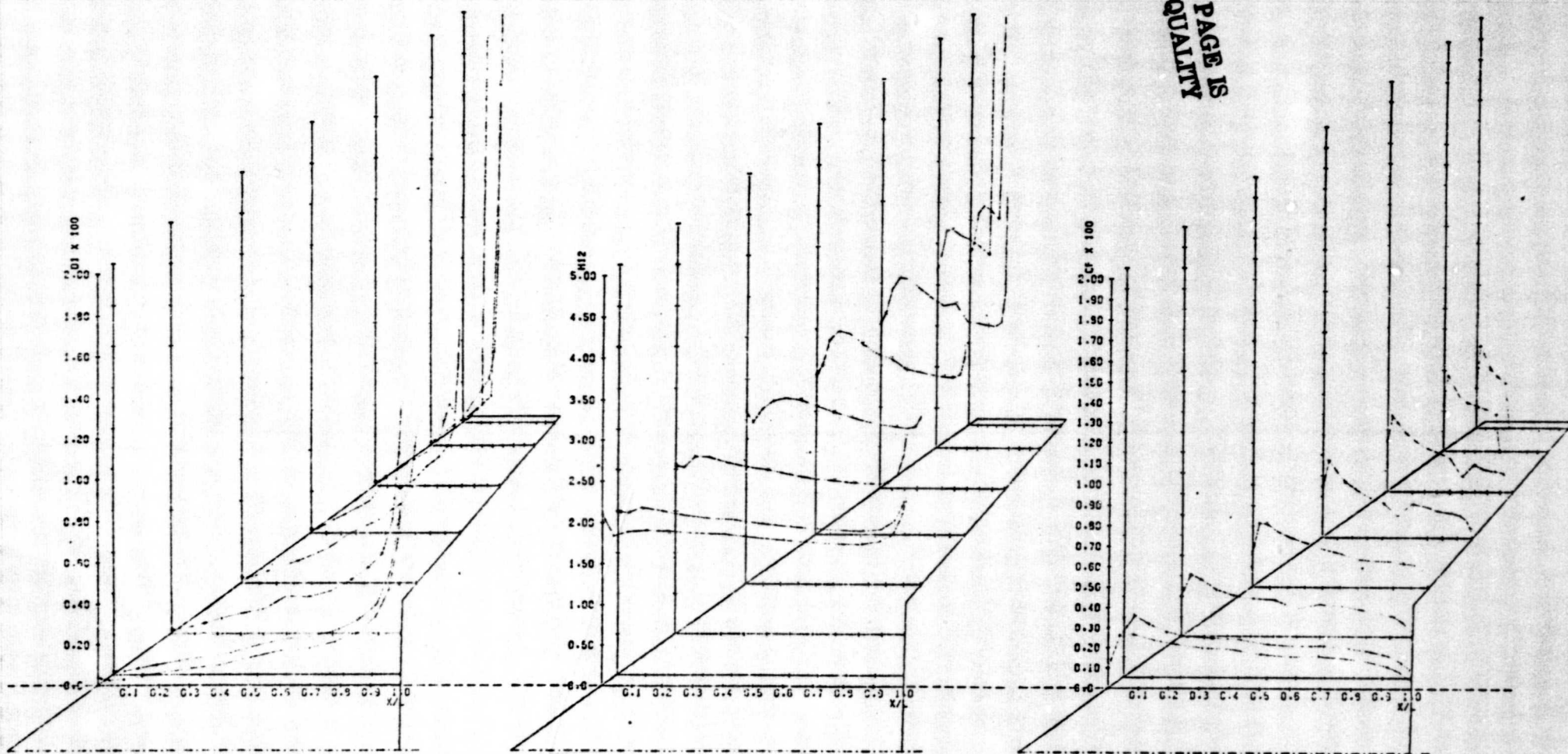


Figure 29: Theoretical Separation Characteristics for the B 10 Preliminary Design

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displacement thickness

shape parameter H_{12}

friction coefficient

Figure 30: Results of a boundary layer calculation for the B 10 X wing

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A300 B2	
M_a	0.78
R [nm]	1950
H [ft]	33000
G_{70} [to]	142
\bar{G} [to]	138
F [m ²]	260
\bar{G}/F	530
Λ	7.73
λ	0.29
φ_{25}	28°
(D/L)%	10.5/10.5

B40X	
M_a	0.78
R [nm]	2900
H [ft]	35000
G_{70} [to]	130
\bar{G} [to]	126
F [m ²]	209
\bar{G}/F	603
Λ	9.0
λ	0.26
φ_{25}	28°
(D/L)%	15.0/12.5

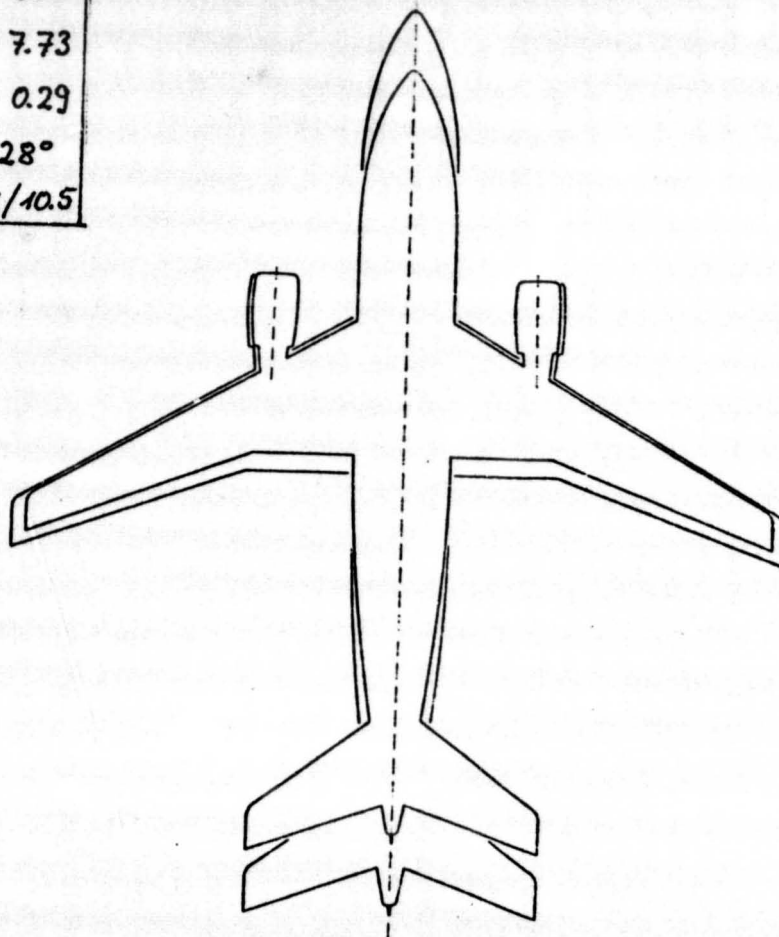


Figure 31: Planform Comparison of A 300 B2 - B 10 X and Project Data

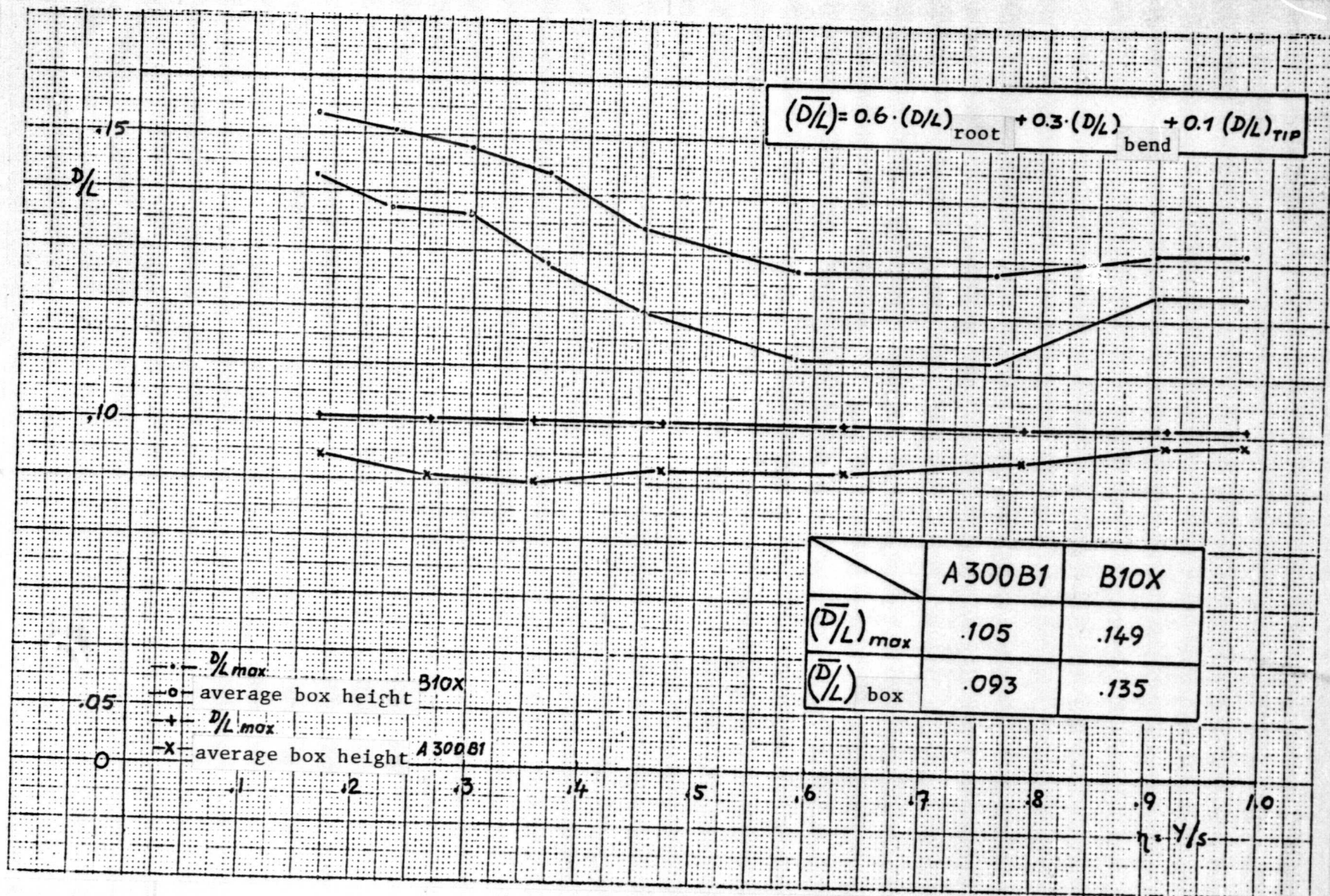


Figure 32: Comparison of Wing Thickness Distribution A 300 B1 - B 10 X

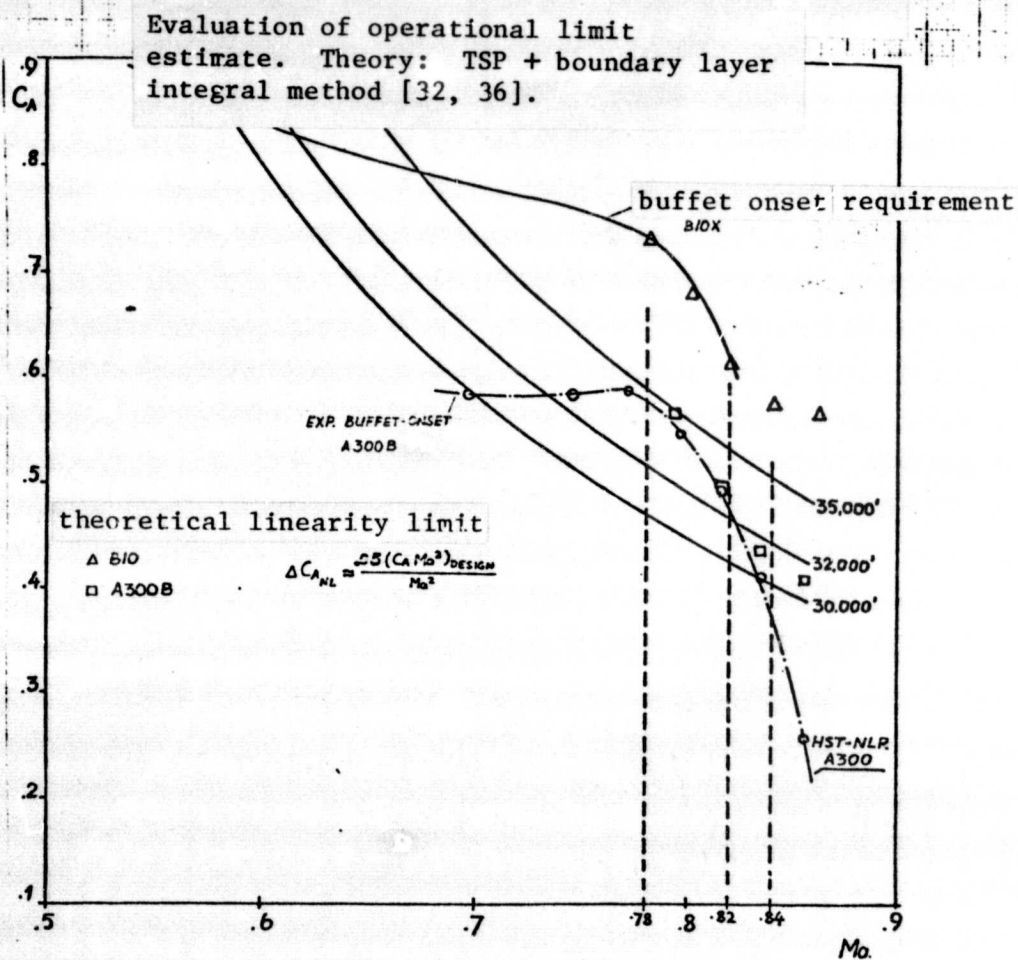
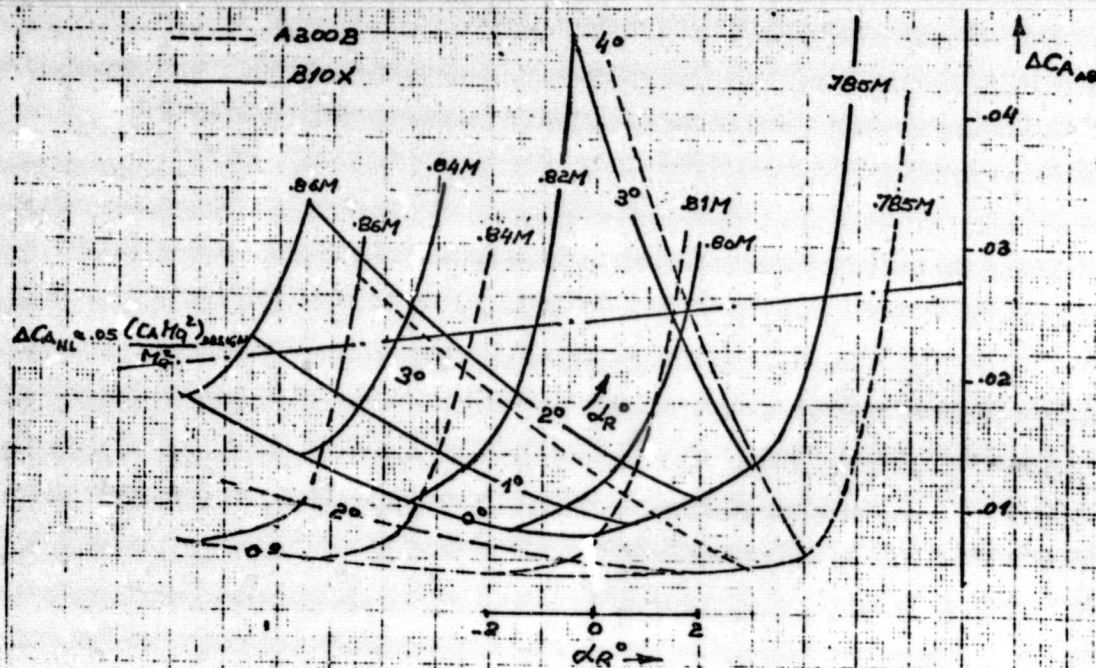


Figure 33: Operating Limit Comparisons, A 300 B - B 10 X

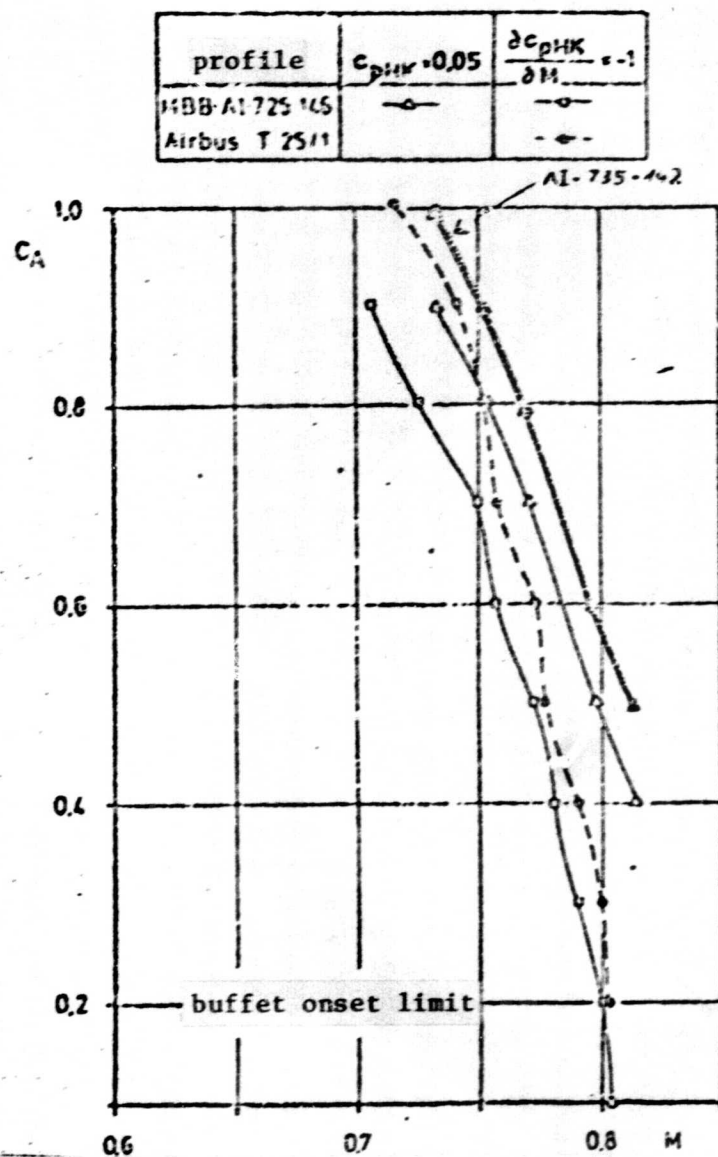
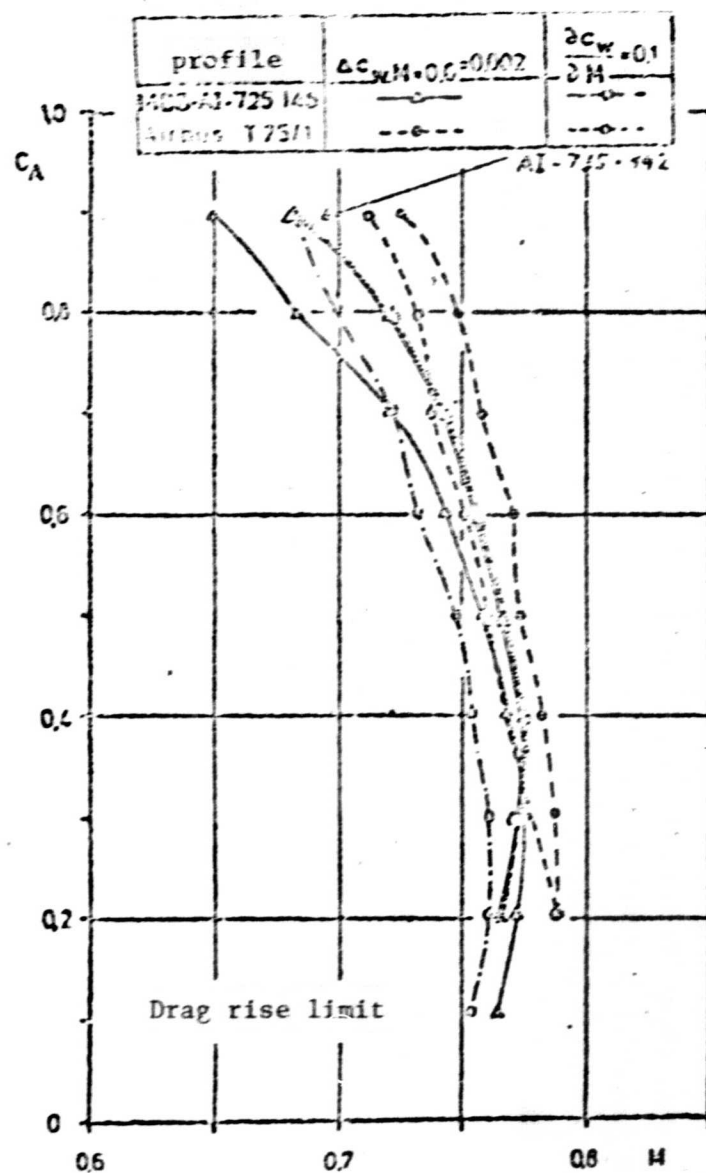


Figure 34: Profile Limiting Curve Comparison A 300 B - B 10 X, Basic Profile over the "Sheared Part".

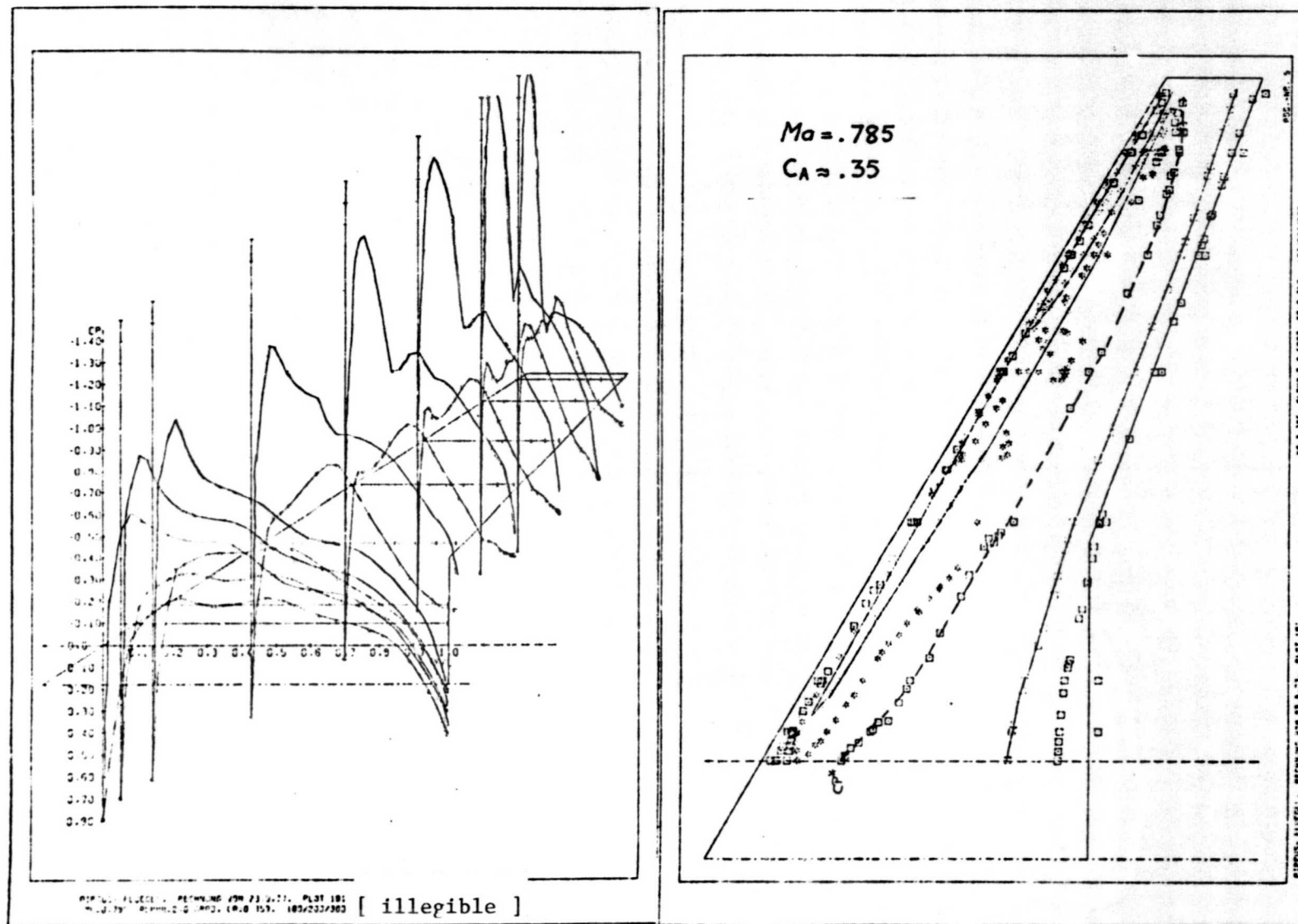


Figure 35: A 300 B Isobar Variation in the Design Range (Transonic Theory)

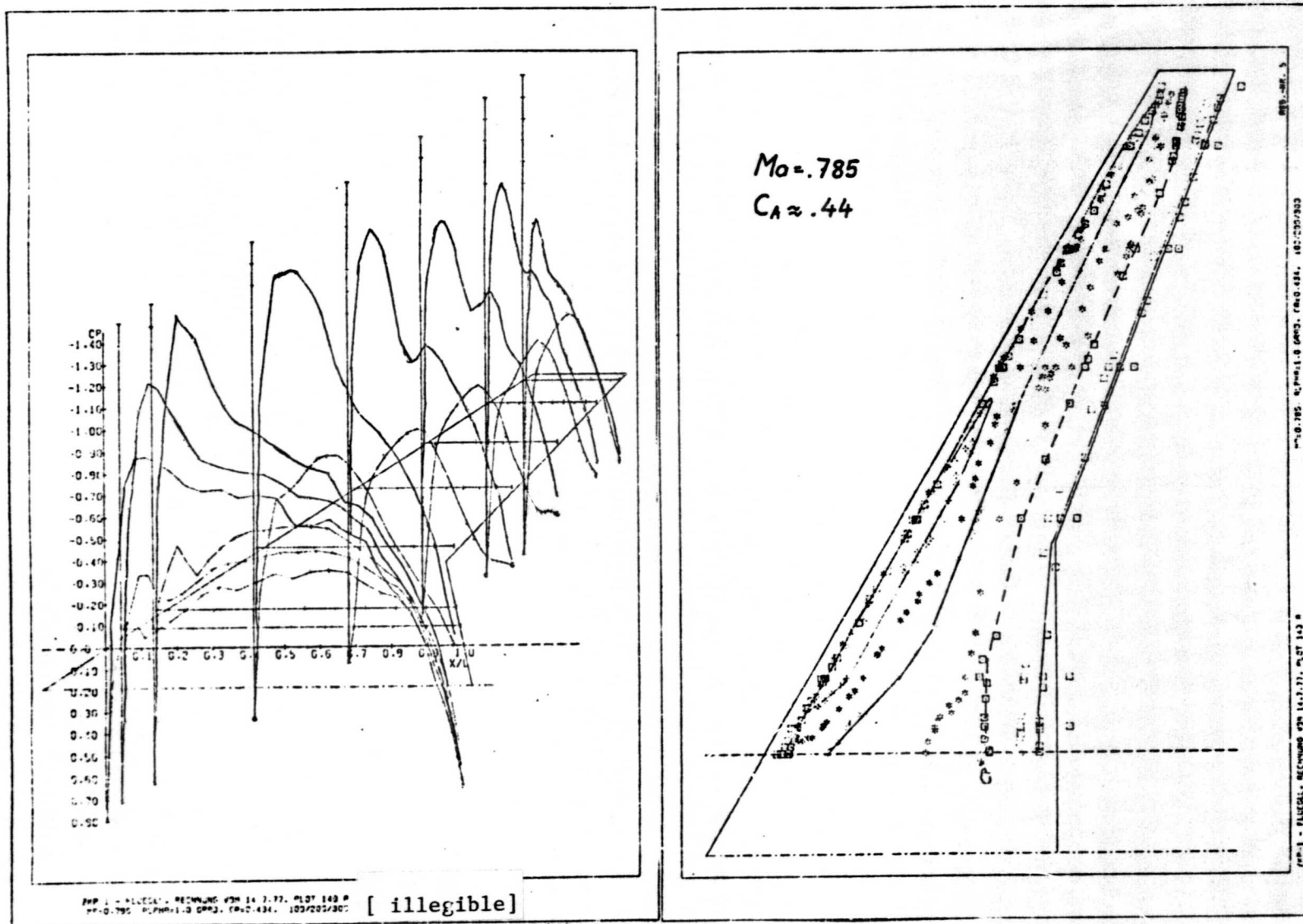
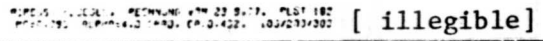
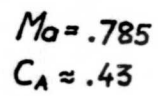


Figure 36: B 10 Isobar Comparison in the Design Range (Transonic Theory)

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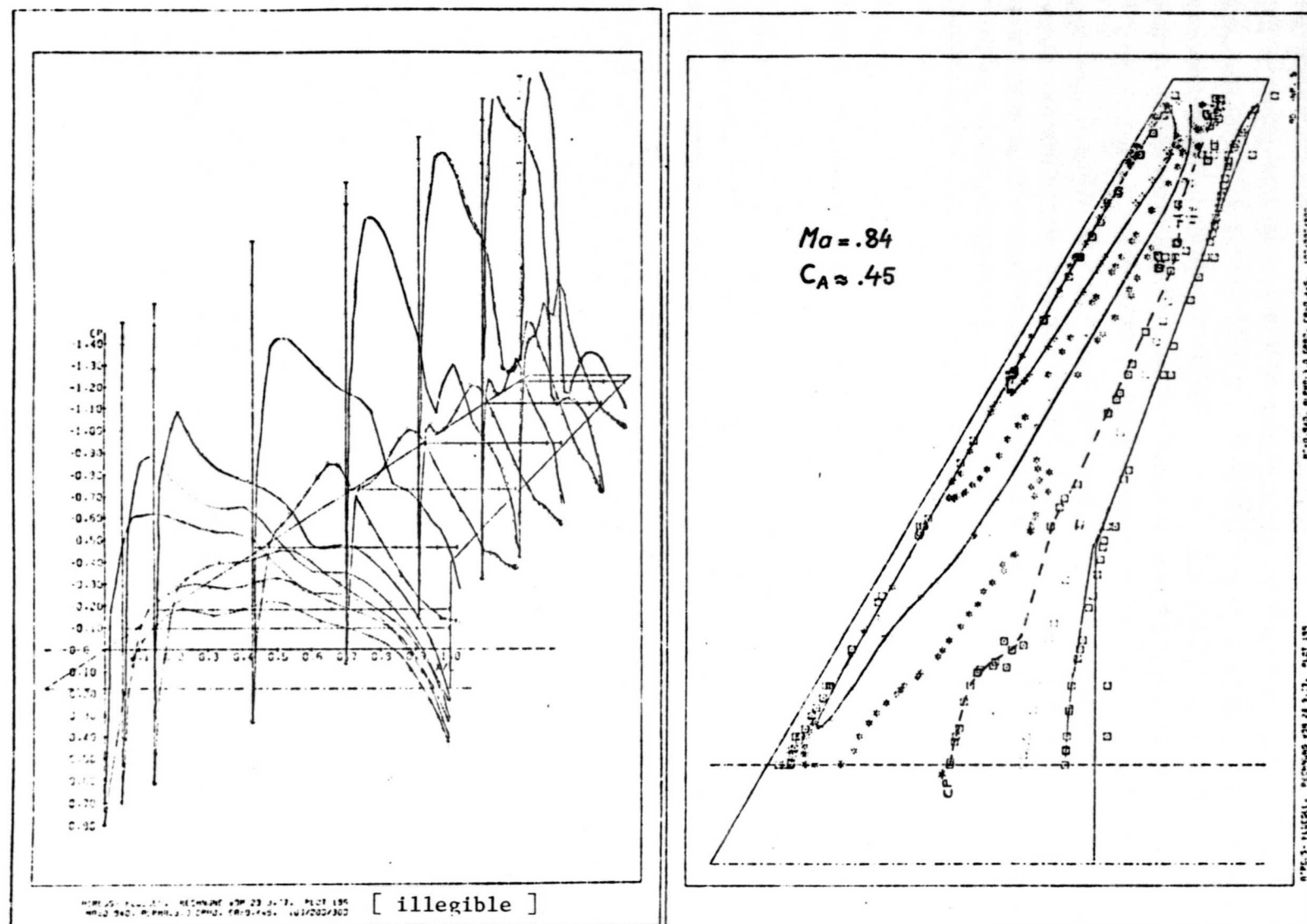
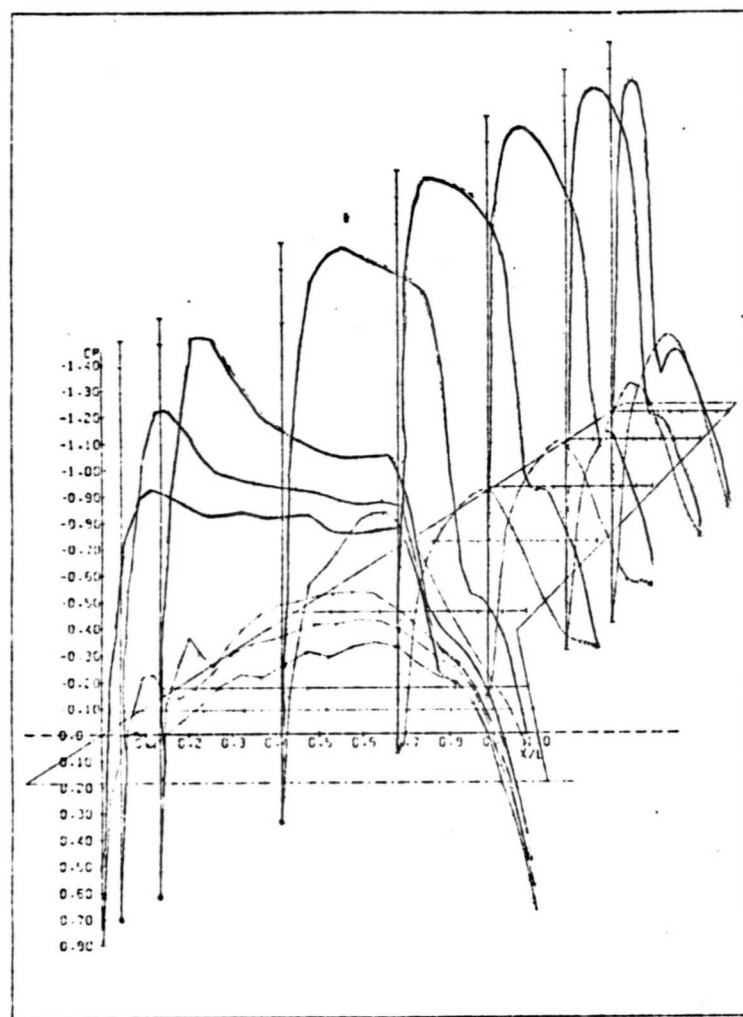
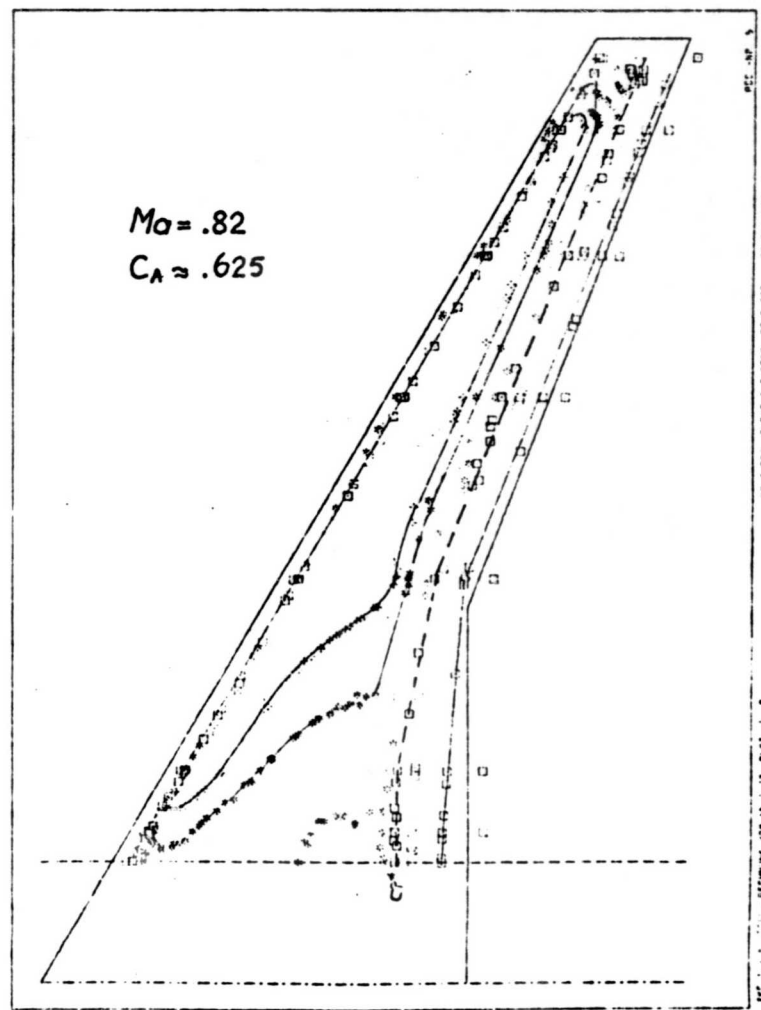


Figure 39: A 300 B Isobar Variation, Transonic Postcalculation



EXP 1 - FLUGEL - RECHNUNG VOM 15.7.77. PLOT 15.9
 WIND 200, ALPHA 2.0 DEG, CH 0.52, 100/200/300



$Ma = .82$
 $C_A \approx .625$

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Figure 40: B 10 Isobar Variation, Transonic Postcalculation